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An enantioselective synthesis of 3-aryl-4-phosphonobutyric acid esters via Cu-catalyzed asymmetric conjugate reduction

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ABSTRACT

The asymmetric conjugate reduction of 3-aryl-4-phosphonobutenoates has been demonstrated which provides an enantioselective synthesis of optically active 3-aryl-4-phosphonobutyric acid esters. A wide range of 3-aryl-4-phosphonobutenoate derivates are reduced with high enantioselectivities (up to 94% ee) using an (*S*)-Segphos/$Cu(OAc)_2 \cdot H_2O$ catalyst system (1 or 5 mol %) in the presence of PMHS and *t*-BuOH. The reduction is influenced by the steric and electronic effects of the substrates.

1. Introduction

The catalytic asymmetric conjugate reduction of α,β-unsaturated compounds offers an efficient and convenient preparation of optically active compounds bearing a stereogenic center at the β-position. Over the past decades, catalysts derived from various transition metals have been developed for achieving this transformation, of which copper hydride species (Cu–H) ligated by chiral ligands have proven to be the most successful.[1] In 1999, Buchwald and co-workers reported the first asymmetric conjugate reduction of α,β-unsaturated esters with a catalyst generated from Tol-BINAP/CuCl/NaOt-Bu in the presence of PMHS (PMHS = polymethylhydrosiloxane).[2] Since then, a series of α,β-unsaturated compounds such as enones,[3] α,β-unsaturated esters,[2,4] α,β-unsaturated phosphonates,[5] α,β-unsaturated lactones and lactams,[6] α,β-unsaturated sulfones,[7] α,β-unsaturated nitrile,[8] nitroalkenes[9] and 2-alkenylheteroarenes[10] have been subjected to conjugate reduction with the Cu–H/diphosphine catalyst system, giving the reduction products with excellent enantioselectivities. Despite these achievements, the development of a new efficient catalyst system with high enantioselectivity, low catalyst loading, and wide substrate scope is still highly desirable from both scientific and practical viewpoints.

Phosphonates are important compounds because of their biological and medical properties.[11] In recent years, a variety of phosphonic acid derivatives such as α-hydroxyphosphonates,[12] β-hydroxyphosphonates,[13] α-aminophosphonates,[14] α-alkylphosphonates,[15] β-alkyl-β-arylphosphonates[16] and 3-phosphonopropanoic acid derivatives[17] have been synthesized by catalytic asymmetric synthesis. However, there are few reports on the enantioselective synthesis of 4-phosphorobutyric acid derivatives[18] although these kinds of chiral compounds are very useful precursors to other optically active phosphonic acid derivatives. Very recently, we[19] reported the enantioselective synthesis of 3-aryl-4-phosphonobutyric acid esters via the first Rh-catalyzed hydrogenation with a *P*-stereogenic BoPhoz-type ligand. However, this method has the disadvantages of demanding reaction conditions and the use of expensive rhodium catalyst. These shortcomings prompted us to seek an alternative method to prepare this compound. Herein, we report the efficient synthesis of 3-aryl-4-phosphonobutyric acid esters via copper-catalyzed asymmetric conjugate reduction of the corresponding 3-aryl-4-phosphonobutenoates in which up to 94% ee was obtained.

2. Results and discussion

We started to investigate the asymmetric conjugate reduction of (*Z*)-methyl 4-(dimethoxyphosphoryl)-3-phenylbut-2-enoate **1a** by surveying a number of diphosphine ligands, copper salts, silanes, and solvents in order to identify a suitable catalyst system. The reactions were carried out in the presence of PMHS (4 equiv) and *t*-BuOH (4 equiv) under catalytic conditions: $Cu(OAc)_2 \cdot H_2O$ (1 mol %), ligands (1.1 mol %) in Et_2O for 24 h and the results are summarized in Table 1. Initially, we screened several chiral diphosphine ligands (Fig. 1). (*S*)-Tol-BINAP, which displayed an excellent performance in the asymmetric conjugate reduction of α,β-unsaturated esters[2] was first tested. To our delight, we found that with (*S*)-Tol-BINAP, the reaction proceeded smoothly and gave the desired product in excellent conversion (98%) and enantioselectivity (92% ee) (entry 1). We then investigated some other chiral biphosphine ligands which were proved to be successful in the asymmetric conjugate reduction, such as (*S*)-BINAP, (*R*)-(*S*)-*t*-Bu-JosiPhos, (*R*)-(*S*)-XyliPhos,

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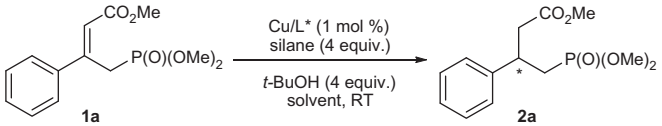
Table 1
Cu-catalyzed asymmetric conjugate reduction of (*Z*)-methyl 4-(diethoxyphosphoryl)-3-phenylbut-2-enoate **1a**[a]



1a 2a

Entry	Ligand	Cu source	Silane	Solvent	Conv.[b] (%)	ee[c] (%)
1	(*S*)-Tol-BINAP	$Cu(OAc)_2{\cdot}H_2O$	PMHS	Et_2O	98	92
2	(*S*)-BINAP	$Cu(OAc)_2{\cdot}H_2O$	PMHS	Et_2O	98	90
3	(*R*)-(*S*)-*t*-Bu-JosiPhos	$Cu(OAc)_2{\cdot}H_2O$	PMHS	Et_2O	98	90
4	(*R*)-(*S*)-XyliPhos	$Cu(OAc)_2{\cdot}H_2O$	PMHS	Et_2O	100	50
5	(*S*)-SegPhos	$Cu(OAc)_2{\cdot}H_2O$	PMHS	Et_2O	100	94
6	(*S*)-SegPhos	$Cu(PPh_3)_3{\cdot}2MeOH$	PMHS	Et_2O	40	—[d]
7	(*S*)-SegPhos	$Cu(OTf)_2$	PMHS	Et_2O	10	—[d]
8	(*S*)-SegPhos	CuOAc	PMHS	Et_2O	5	—[d]
9	(*S*)-SegPhos	$CuF_2{\cdot}H_2O$	PMHS	Et_2O	10	—[d]
10	(*S*)-SegPhos	$Cu(OAc)_2{\cdot}H_2O$	Et_3SiH	Et_2O	20	—[d]
11	(*S*)-SegPhos	$Cu(OAc)_2{\cdot}H_2O$	$PHSiH_3$	Et_2O	100	93
12	(*S*)-SegPhos	$Cu(OAc)_2{\cdot}H_2O$	$PHSiH_2$	Et_2O	100	77
13	(*S*)-SegPhos	$Cu(OAc)_2{\cdot}H_2O$	TMDS	Et_2O	96	91
14	(*S*)-SegPhos	$Cu(OAc)_2{\cdot}H_2O$	PMHS	Toluene	80	87
15	(*S*)-SegPhos	$Cu(OAc)_2{\cdot}H_2O$	PMHS	MeOH	10	24
16	(*S*)-SegPhos	$Cu(OAc)_2{\cdot}H_2O$	PMHS	THF	62	90
17	(*S*)-SegPhos	$Cu(OAc)_2{\cdot}H_2O$	PMHS	CH_2Cl_2	32	92

[a] All reactions were performed at 1 mol % of catalyst loadings prepared in situ from Cu-precursor and 1.1 equiv of chiral diphosphine ligand with 0.5 mmol of substrate **1a** at room temperature in 2 mL of solvent for 24 h.
[b] Degree of conversion was determined by GC.
[c] Enantiomeric excesses were determined by chiral HPLC.
[d] Not determined due to low conversion.

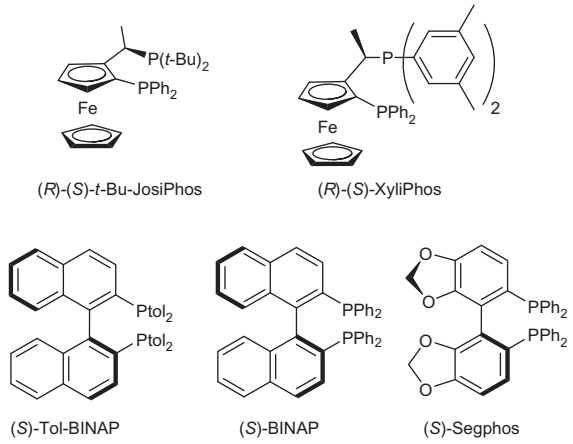


Figure 1. Chiral diphosphine ligands evaluated in the asymmetric conjugate reduction.

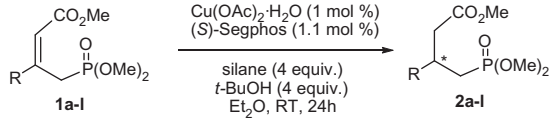
and (*S*)-SegPhos (entries 2–5). This study identified (*S*)-SegPhos as the best ligand in terms of conversion and enantioselectivity; we then retained it for the next round of optimization involving variation of copper salts, silanes, and solvents. Optimization of the copper salts such as $Cu(PPh_3)_3{\cdot}2MeOH$, $Cu(OTf)_2$, $CuF_2{\cdot}H_2O$, and CuOAc was unsuccessful, giving very low reaction activity (entries 6–9). Silanes were then screened and then revealed that PMHS, $PHSiH_3$, and 1,1,3,3-tetramethyldisiloxane (TMDS) gave similar results (entries 1, 11, and 13), although PMHS was slightly superior with respect to enantioselectivity (entry 1). Solvent effects were also tested (entries 14–17) and Et_2O was proved to be the best solvent.

These promising results promoted us to investigate the substrate scope and a variety of 3-aryl-4-phosphonobutenoates were then examined. The details of the results are summarized in Table 2, and clearly demonstrate that the enantioselectivities of the reaction were influenced by steric and electronic effects. Generally speaking, substrates with an *ortho*-methoxy in the phenyl ring tended to be reduced with low reactivity and enantioselectivity than those with a *meta*- or *para*-methoxy group (entries 2–4). The electronic properties of the *para*-substituent on the phenyl ring of the substrates also had an important influence on the enantioselectivities. The substrates with an electron-withdrawing group gave better enantioselectivities than those with an electron-donating group (entries 4–8). However, the reduction of substrate **1h** with a *para*-nitro group on the phenyl ring required a larger catalyst loading and higher temperatures in order to reach complete conversion (entry 8). Surprisingly, substrates with a *meta*- electron-withdrawing group on the phenyl ring were reduced with moderate ee values (entry 9). Reduction of 2-naphthyl substrate also gave excellent ee values (entry 10). Meanwhile, a heteroaromatic derivative was also suitable for this reaction (entry 11). However, low conversion was achieved in the reduction of 3-alkyl-substituted substrate **1l** (entry 12). These results indicated that the 3-aryl-4-phosphonobutenoate derivatives, which bear substituted groups such as methoxy, fluoro, chloro, bromo, and nitro at the *ortho*, *meta*, and *para* positions, as well as naphthyl and heteroaromatic derivates, all reacted smoothly to afford the corresponding 3-aryl-4-phosphonobutyric acid esters in good to excellent ee values.

3. Conclusion

In conclusion, we have developed a copper-catalyzed asymmetric conjugate reduction of 3-aryl-4-phosphonobutenoates that provides an enantioselective synthesis of optically active 3-aryl-4-phosphonobutyric acid esters. A wide range of 3-aryl-4-phosphonobutenoates were reduced with high enantioselectivities (up to 94% ee) using a (*S*)-Segphos/$Cu(OAc)_2{\cdot}H_2O$ catalyst system (1 or 5 mol %) in the presence of PMHS and *t*-BuOH. The reduction was influenced by steric and electronic effects. Generally, substrates having an electron-withdrawing group at the *para*-position of the phenyl ring were reduced in higher ee value than those with an electron-donating group. Further applications of this methodology are in progress.

Table 2
Cu-catalyzed asymmetric conjugate reduction of 3-aryl-4-phosphonobutenoates with (*S*)-Segphos[a]



Entry	Substrate (R)	Yield[b] (%)	ee[c] (%)
1	***Z*-1a**: R = C_6H_5	95	94 (−)
2[d]	***Z*-1b**: R = 2-MeO-C_6H_4	77	68 (−)
3	***Z*-1c**: R = 3-MeO-C_6H_4	90	93 (−)
4	***Z*-1d:** R = 4-MeO-C_6H_4	95	83 (−)
5	***Z*-1e**: R = 4-Br-C_6H_4	93	92 (−)
6	***Z*-1f**: R = 4-Cl-C_6H_4	94	92 (*S*)
7	***Z*-1g**: R = 4-F-C_6H_4	86	91 (−)
8[d]	***Z*-1h:** R = 4-NO_2-C_6H_4	95	90 (−)
9[e]	***Z*-1i:** R = 3-Cl-C_6H_4	95	72 (−)
10	***Z*-1j**: R = 2-naphthyl	94	90 (−)
11[d]	***Z*-1k**: R = 2-thienyl	85	91 (−)
12	***Z*/*E*-1l**: R = Me	—[f]	—[f]

[a] Reaction conditions: substrate **1** (0.5 mmol), $Cu(OAc)_2·H_2O$ (1 mol %), (*S*)-Segphos (1.1 mol %), PMHS (4 equiv), *t*-BuOH (4 equiv) in Et_2O at room temperature for 24 h.
[b] Isolated yield.
[c] The ee values were determined by HPLC on a Chiralcel AS-H chiral column. The absolute configuration was determined by comparison of the sign of the specific rotation with reported data.
[d] Reaction was performed at 5 mol % catalyst loading and at 50 °C.
[e] Reaction was performed at 5 mol % catalyst loading and at room temperature.
[f] Not determined due to low conversion.

4. Experimental

4.1. General

All reactions were carried out under nitrogen atmosphere using standard Schlenk techniques. The 3-aryl-4-phosphonobutenoate substrates were synthesized according to a reported procedure.[19] All solvents were dried and degassed by standard methods and stored under nitrogen. All other chemicals were obtained commercially. ^{1}H NMR and ^{31}P NMR was recorded at Bruker DPX400 NMR spectrometer. Chemical shifts are expressed in δ value (ppm) using tetramethylsilane (TMS) as an internal standard. HPLC analysis was performed on an Agilent 1100 series instrument with a chiralcel AS-H chiral column.

4.2. General procedure for the Cu-catalyzed asymmetric conjugate reduction

Copper salt (0.005 mmol) and ligand (0.0055 mmol) were added into an oven-dried Schlenk tube. Then, dry Et_2O (2.0 mL) was added under N_2. The mixture was stirred at room temperature for 30 min to give a solution. Next, PMHS (120 μL, 2.0 mmol) was added to the reaction mixture and stirred for 30 min. The substrate (0.50 mmol) was then added, followed by *t*-BuOH (190 μL, 2.0 mmol). The reaction was sealed, and stirred for 24 h. The reaction mixture was quenched with saturated aqueous ammonium chloride solution and the aqueous layer was extracted with AcOEt (3 × 10 mL). The combined organic layers were washed with brine, dried over Na_2SO_4, and concentrated. The product was purified by chromatography on silica gel.

4.2.1. Methyl 4-(dimethoxyphosphoryl)-3-phenyl-butanoate 2a[19]

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.08–2.29 (m, 2H), 2.65–2.71 (m, 1H), 2.87–2.93 (m, 1H), 3.53–3.59 (m, 10H), 7.20–7.25 (m, 3H), 7.27–7.33 (m, 2H); ^{31}P NMR (162 MHz, $CDCl_3$): δ 31.8. $[\alpha]_D^{20} = -0.5$ (*c* 1.58, $CHCl_3$). HPLC analysis: Chiralcel AS-H column; flow rate: 1.0 mL/min; eluent: *n*-hexane/*i*-PrOH(90:10); detection at 210 nm; t_1 = 42.85 min(major enantiomer), t_2 = 47.56 min(minor enantiomer); ee = 94%.

4.2.2. Methyl 4-(dimethoxyphosphoryl)-3-(2-methoxy-phenyl)-butanoate 2b[19]

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.25–2.35 (m, 2H), 2.80–2.86 (m, 1H), 2.91–2.96 (m, 1H), 3.55 (s, 3H), 3.57 (s, 6H), 3.72–3.79 (m, 1H), 3.84 (s, 3H), 6.85–6.91 (m, 2H), 7.18–7.22 (m 2H); ^{31}P NMR (162 MHz, $CDCl_3$): δ 32.9 $[\alpha]_D^{20} = -1.5$ (*c* 1.21, $CHCl_3$). HPLC analysis: Chiralcel AS-H column; flow rate: 1.0 mL/min; eluent: *n*-hexane/*i*-PrOH(90:10); detection at 210 nm; t_1 = 47.60 min(minor enantiomer), t_2 = 51.77 min(major enantiomer); ee = 68%.

4.2.3. Methyl 4-(dimethoxyphosphoryl)-3-(3-methoxy-phenyl)-butanoate 2c[19]

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.07–2.27 (m, 2H), 2.64–2.70 (m, 1H), 2.87–2.93 (m, 1H), 3.50–3.61 (m, 10H), 3.79 (s, 3H), 6.75–6.84 (m, 3H), 7.22 (t, *J* = 8.0 Hz 1H); ^{31}P NMR (162 MHz, $CDCl_3$): δ 31.7 $[\alpha]_D^{20} = -1.2$ (*c* 1.61, $CHCl_3$). HPLC analysis: Chiralcel AS-H column; flow rate: 1.0 mL/min; eluent: *n*-hexane/*i*-PrOH(90:10); detection at 210 nm; t_1 = 69.53 min(major enantiomer), t_2 = 75.45 min(minor enantiomer); ee = 93%.

4.2.4. Methyl 4-(dimethoxyphosphoryl)-3-(4-methoxy-phenyl)-butanoate 2d[19]

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.05–2.26 (m, 2H), 2.61–2.67 (m, 1H), 2.84–2.89 (m, 1H), 3.46–3.60 (m, 10H), 3.78 (s, 3H), 6.84 (d, *J* = 8.0 Hz, 2H), 7.16 (d, *J* = 8.0 Hz 2H); ^{31}P NMR (162 MHz, $CDCl_3$): δ 31.8 $[\alpha]_D^{20} = -1.1$ (*c* 1.35, $CHCl_3$). HPLC analysis: Chiralcel AS-H column; flow rate: 1.0 mL/min; eluent: *n*-hexane/*i*-PrOH(90:10); detection at 210 nm; t_1 = 66.24 min(major enantiomer), t_2 = 80.29 min(minor enantiomer); ee = 83%.

4.2.5. Methyl 3-(4-bromophenyl)-4-(dimethoxy-phosphoryl)-butanoate 2e[19]

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.05–2.24 (m, 2H), 2.62–2.68 (m, 1H), 2.86–2.91 (m, 1H), 3.50–3.62 (m, 10H), 7.13 (t, *J* = 8.0 Hz 2H), 7.43 (t, *J* = 8.0 Hz 2H); ^{31}P NMR (162 MHz, $CDCl_3$): δ 31.2. $[\alpha]_D^{20} = -3.9$ (*c* 1.23, $CHCl_3$). HPLC analysis: Chiralcel AS-H column; flow rate: 1.0 mL/min; eluent: *n*-hexane/*i*-PrOH(90:10); detection at 210 nm; t_1 = 41.23 min(major enantiomer), t_2 = 50.63 min(minor enantiomer); ee = 92%.

4.2.6. Methyl 3-(4-chlorophenyl)-4-(dimethoxy-phosphoryl)-butanoate 2f[19]

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.05–2.24 (m, 2H), 2.62–2.68 (m, 1H), 2.86–2.91 (m, 1H), 3.51–3.62 (m, 10H), 7.19(s, *J* = 8.0 Hz 2H), 7.27–7.29 (m, 2H); ^{31}P NMR (162 MHz, $CDCl_3$): δ 31.3. $[\alpha]_D^{20} = -3.6$ (*c* 1.14, $CHCl_3$). HPLC analysis: Chiralcel AS-H column; flow rate: 1.0 mL/min; eluent: *n*-hexane/*i*-PrOH(90:10); detection at 210 nm; t_1 = 38.58 min(major enantiomer), t_2 = 45.87 min(minor enantiomer); ee = 92%.

4.2.7. Methyl 4-(dimethoxyphosphoryl)-3-(4-fluoro-phenyl)-butanoate 2g[19]

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.06–2.24 (m, 2H), 2.61–2.67 (m, 1H), 2.85–2.90 (m, 1H), 3.52–3.61 (m, 10H), 7.00 (t, *J* = 8.0 Hz 2H), 7.20–7.22 (m, 2H); ^{31}P NMR (162 MHz, $CDCl_3$): δ 31.5. $[\alpha]_D^{20} = -1.8$ (*c* 1.10, $CHCl_3$). HPLC analysis: Chiralcel AS-H column; flow rate: 1.0 mL/min; eluent: *n*-hexane/*i*-PrOH(90:10); detection at 210 nm; t_1 = 42.49 min(major enantiomer), t_2 = 47.96 min(minor enantiomer); ee = 91%.

4.2.8. Methyl 4-(dimethoxyphosphoryl)-3-(4-nitro-phenyl)-butanoate 2h[19]

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.00–2.20 (m, 2H), 2.54–2.60 (m, 1H), 2.77–2.83 (m, 1H), 3.38–3.45 (m, 1H), 3.50–3.56 (m, 9H), 6.59 (d, J = 8.0 Hz 2H), 6.98 (d, J = 8.0 Hz 2H); ^{31}P NMR (162 MHz, $CDCl_3$): δ 32.3. $[\alpha]_D^{20} = -3.4$ (c 1.45, $CHCl_3$). HPLC analysis: Chiralcel AS-H column; flow rate: 1.0 mL/min; eluent: n-hexane/i-PrOH(80:20); detection at 210 nm; t_1 = 48.70 min(major enantiomer), t_2 = 64.85 min(minor enantiomer); ee = 90%.

4.2.9. Methyl 3-(3-chlorophenyl)-4-(dimethoxy-phosphoryl)-butanoate 2i

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.03–2.25 (m, 2H), 2.62–2.68 (m, 1H), 2.86–2.92 (m, 1H), 3.56–3.61 (m, 10H), 7.13–7.26 (m, 4H); ^{31}P NMR (162 MHz, $CDCl_3$): δ 31.0; ^{13}C NMR (100 MHz, $CDCl_3$): δ 31.0 (d, J = 139.2 Hz), 36.2 (d, J = 3.1 Hz), 41.0 (d, J = 11.0 Hz), 51.6, 52.0 (d, J = 6.5 Hz), 52.3 (d, J = 6.5 Hz), 125.5, 127.2, 127.4, 129.8, 134.2, 145.0 (d, J = 9.7 Hz), 171.4; $[\alpha]_D^{20} = -2.4$ (c 1.50, $CHCl_3$). HPLC analysis: Chiralcel AS-H column; flow rate: 1.0 mL/min; eluent: n-hexane/i-PrOH(90:10); detection at 215 nm; t_1 = 47.34 min(major enantiomer), t_2 = 50.83 min(minor enantiomer); ee = 72%.

4.2.10. Methyl 4-(dimethoxyphosphoryl)-3-(2-naphthyl)-butanoate 2j[19]

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.18–2.37 (m, 2H), 2.75–2.81 (m, 1H), 2.97–3.02 (m, 1H), 3.51–3.58 (m, 9H), 3.71–3.78 (m, 1H), 7.37 (d, J = 8.0 Hz 1H), 7.44–7.46 (m, 2H), 7.70 (s, 1H), 7.80 (d, J = 8.0 Hz 3H); ^{31}P NMR (162 MHz, $CDCl_3$): δ 31.8. $[\alpha]_D^{20} = -2.4$ (c 1.02, $CHCl_3$). HPLC analysis: Chiralcel AS-H column; flow rate: 1.0 mL/min; eluent: n-hexane/i-PrOH(90:10); detection at 210 nm; t_1 = 52.18 min(major enantiomer), t_2 = 57.16 min(minor enantiomer); ee = 90%.

4.2.11. Methyl 4-(dimethoxyphosphoryl)-3-(2-thienyl)-butanoate 2k[19]

^{1}H NMR (400 MHz, $CDCl_3$): δ 2.16–2.34 (m, 2H), 2.69–2.75 (m, 1H), 2.93–2.98 (m, 1H), 3.57–3.66 (m, 9H), 3.86–3.93 (m, 1H), 6.91–6.92 (m, 2H), 7.16–7.17 (m, 1H); ^{31}P NMR (162 MHz, $CDCl_3$): δ 31.0. $[\alpha]_D^{20} = -3.8$ (c 1.86, $CHCl_3$). HPLC analysis: Chiralcel AS-H column; flow rate: 1.0 mL/min; eluent: n-hexane/i-PrOH(90:10); detection at 210 nm; t_1 = 40.88 min(minor enantiomer), t_2 = 45.81 min(major enantiomer); ee = 91%.

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References

1. (a) Rendler, S.; Oestreich, M. *Angew. Chem., Int. Ed.* **2007**, *46*, 498–504; (b) Deutsch, C.; Krause, N.; Lipshutz, B. H. *Chem. Rev.* **2008**, *108*, 2916–2927.
2. Appella, D. H.; Moritani, Y.; Shintani, R.; Ferreira, E. M.; Buchwald, S. L. *J. Am. Chem. Soc.* **1999**, *121*, 9473–9474.
3. (a) Moritani, Y.; Appella, D. H.; Jurkauskas, V.; Buchwald, S. L. *J. Am. Chem. Soc.* **2000**, *122*, 6797–6798; (b) Jurkauskas, V.; Buchwald, S. L. *J. Am. Chem. Soc.* **2002**, *124*, 2892–2893; (c) Lipshutz, B. H.; Servesko, J. M. *Angew. Chem., Int. Ed.* **2003**, *42*, 4789–4792; (d) Lipshutz, B. H.; Frieman, B. A.; Tomaso, A. E., Jr. *Angew. Chem., Int. Ed.* **2006**, *45*, 1259–1264.
4. (a) Hughes, G.; Kimura, M.; Buchwald, S. L. *J. Am. Chem. Soc.* **2003**, *125*, 11253–11258; (b) Lipshutz, B. H.; Servesko, J. M.; Taft, B. R. *J. Am. Chem. Soc.* **2004**, *126*, 8352–8353; (c) Rainka, M. P.; Aye, Y.; Buchwald, S. L. *Proc. Natl. Acad. Sci. U.S.A.* **2004**, *101*, 5821–5823; (d) Deng, J.; Hu, X.-P.; Huang, J.-D.; Yu, S.-B.; Wang, D.-Y.; Duan, Z.-C.; Zheng, Z. *J. Org. Chem.* **2008**, *73*, 6022–6024; (e) Hou, C.-J.; Guo, W.-L.; Hu, X.-P.; Deng, J.; Zheng, Z. *Tetrahedron Asymmetry* **2011**, *22*, 195–199.
5. Duan, Z.-C.; Hu, X.-P.; Wang, D.-Y.; Yu, S.-B.; Zheng, Z. *Tetrahedron Lett.* **2009**, *50*, 6720–6722.
6. (a) Lipshutz, B. H.; Frieman, B. A.; Unger, J. B.; Nihan, D. M. *Can. J. Chem.* **2005**, *83*, 606–614; (b) Rainka, M. P.; Milne, J. E.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2005**, *44*, 6177–6180.
7. Llamas, T.; Arrayás, R. G.; Carretero, J. C. *Angew. Chem., Int. Ed.* **2007**, *46*, 3329–3332.
8. (a) Lee, D.; Kim, D.; Yun, J. *Angew. Chem., Int. Ed.* **2006**, *45*, 2785–2787; (b) Lee, D.; Yang, Y.; Yun, J. *Org. Lett.* **2007**, *9*, 2749–2751.
9. (a) Czekelius, C.; Carreira, E. M. *Angew. Chem., Int. Ed.* **2003**, *42*, 4793–4795; (b) Czekelius, C.; Carreira, E. M. *Org. Process Res. Dev.* **2007**, *11*, 633–636.
10. Rupnicki, L.; Saxena, A.; Lam, H. W. *J. Am. Chem. Soc.* **2009**, *131*, 10386–10387.
11. (a) Hilderbrand, R. L. *The Role of Phosphonates in Living Systems*; CRC Press: Boca Raton, 1983; (b) Patek, D. V.; Rielly-Gauvin, K.; Ryono, D. E. *Tetrahedron Lett.* **1990**, *31*, 5587–5590; (c) Wang, C.-L. J.; Taylor, T. L.; Mical, A. J.; Spitz, S.; Reilly, T. M. *Tetrahedron Lett.* **1992**, *33*, 7667–7670; (d) Patek, D. V.; Rielly-Gauvin, K.; Ryono, D. E.; Free, E. W., Jr. *J. Med. Chem.* **1995**, *38*, 4557–4569; (e) Savignac, P.; Iorga, B. *Morden Phosphonate Chemistry*; CRC Press: Boca Raton, 2003.
12. (a) Wang, D.-Y.; Hu, X.-P.; Huang, J.-D.; Deng, J.; Yu, S.-B.; Duan, Z.-C.; Xu, X.-F.; Zheng, Z. *Angew. Chem., Int. Ed.* **2007**, *46*, 7810–7813; (b) Wang, D.-Y.; Huang, J.-D.; Hu, X.-P.; Deng, J.; Yu, S.-B.; Duan, Z.-C.; Zheng, Z. *J. Org. Chem.* **2008**, *73*, 2011–2014; (c) Albrecht, Ł.; Albrecht, A.; Krawczyk, H.; Jørgensed, K. A. *Chem. Eur. J.* **2010**, *16*, 28–48; (d) Perera, S.; Naganaboina, V. K.; Wang, L.; Zhang, B.; Guo, Q.; Rout, L.; Zhao, C.-G. *Adv. Synth. Catal.* **2011**, *353*, 1729–1734.
13. (a) Kitamura, M.; Tokunaga, M.; Noyori, R. *J. Am. Chem. Soc.* **1995**, *117*, 2931–2932; (b) Meier, C.; Laux, W. H. *Tetrahedron: Asymmetry* **1995**, *6*, 1089–1092; (c) Vargas, S.; Suárez, A.; Álvarez, E.; Pizzano, A. *Chem. Eur. J.* **2008**, *14*, 9856–9859.
14. (a) Dwars, T.; Schmidt, U.; Fischer, C.; Grassert, I.; Kempe, R.; Fröhlich, R.; Drauz, K.; Oehme, G. *Angew. Chem., Int. Ed.* **1998**, *37*, 2851–2853; (b) Armstrong, A.; Deacon, N.; Donald, C. *Synlett* **2011**, 2347–2350; (c) Pham, T. S.; Czirok, J. B.; Balázs, L.; Pál, K.; Kubinyi, M.; Bitter, I.; Jászay, Z. *Tetrahedron: Asymmetry* **2011**, 22, 480–486.
15. (a) Wang, D.-Y.; Hu, X.-P.; Deng, J.; Yu, S.-B.; Duan, Z.-C.; Zheng, Z. *J. Org. Chem.* **2009**, *74*, 4408–4410; (b) Cheruku, P.; Paptchikhine, A.; Church, T. L.; Andersson, P. G. *J. Am. Chem. Soc.* **2009**, *131*, 8285–8289.
16. (a) Duan, Z.-C.; Hu, X.-P.; Wang, D.-Y.; Huang, J.-D.; Yu, S.-B.; Deng, J.; Zheng, Z. *Adv. Synth. Catal.* **2008**, *350*, 1979–1983; (b) Duan, Z.-C.; Hu, X.-P.; Zhang, C.; Wang, D.-Y.; Yu, S.-B.; Zheng, Z. *J. Org. Chem.* **2009**, *74*, 9191–9194.
17. (a) Badkar, P. A.; Rath, N. P.; Spilling, C. D. *Org. Lett.* **2007**, *9*, 3619–3622; (b) Wang, D.-Y.; Hu, X.-P.; Hou, C.-J.; Deng, J.; Yu, S.-B.; Duan, Z.-C.; Huang, J.-D.; Zheng, Z. *Org. Lett.* **2009**, *11*, 3226–3229.
18. (a) Fernández, M. C.; Díaz, A.; Guillín, J. J.; Blanco, O.; Ruiz, M.; Ojea, V. *J. Org. Chem.* **2006**, *71*, 6958–6974; (b) Selvam, C.; Goudet, C.; Oueslati, N.; Pin, J.-P.; Acher, F. C. *J. Med. Chem.* **2007**, *50*, 4656–4664; (c) Liu, F.; Park, J.-E.; Lee, K. S.; Burke, T. R., Jr. *Tetrahedron* **2009**, *65*, 9673–9679.
19. Duan, Z.-C.; Hu, X.-P.; Zhang, C.; Zheng, Z. *J. Org. Chem.* **2010**, *75*, 8319–8321.