DOI: 10.1002/adsc.200900888

Palladium(II) Complexes of C_2-Bridged Chiral Diphosphines: Application to Enantioselective Carbonyl-Ene Reactions

He-Kuan Luo,[a,*] Yuan-Ling Woo,[a] Herbert Schumann,[b] Chacko Jacob,[a] Martin van Meurs,[a] Hai-Yan Yang,[a] and Yen-Ting Tan[a]

[a] Institute of Chemical and Engineering Sciences, A*STAR (Agency for Science, Technology and Research), 1 Pesek Road, Jurong Island, Singapore 627833
Fax: (+65)-6316-6182; e-mail: luo_hekuan@ices.a-star.edu.sg
[b] Institut für Chemie, Technische Universität Berlin, Straße des 17. Juni 135, 10623 Berlin, Germany

Received: December 22, 2009; Revised: April 19, 2010; Published online: May 5, 2010

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/adsc.200900888.

Abstract: (11b*R*,11′b*R*)-4,4′-(1,2-Phenylene)bis[4,5-dihydro-3*H*-dinaphtho[2,1-*c*:1′,2′-*e*]phosphepin] [abbreviated as (*R*)-BINAPHANE], (3*R*,3′*R*,4*S*,4′*S*,11b*S*,11′b*S*)-4,4′-bis(1,1-dimethylethyl)-4,4′,5,5′-tetrahydro-3,3′-bi-3*H*-dinaphtho[2,1-*c*:1′,2′-*e*]phosphepin [(*S*)-BINAPINE], (1*S*,1′*S*,2*R*,2′*R*)-1,1′-bis(1,1-dimethylethyl)-2,2′-biphospholane [(*S,S,R,R*)-TANGPHOS] and (2*R*,2′*R*,5*R*,5′*R*)-1,1′-(1,2-phenylene)bis[2,5-bis(1-methylethyl)phospholane] [(*R,R*)-*i*-Pr-DUPHOS] are C_2-bridged chiral diphosphines that form stable complexes with palladium(II) and platinum(II) containing a five-membered chelate ring. The Pd(II)-BINAPHANE catalyst displayed good to excellent enantioselectivities with *ee* values as high as 99.0% albeit in low yields for the carbonyl-ene reaction between phenylglyoxal and alkenes. Its Pt(II) counterpart afforded improved yields while retaining satisfactory enantioselectivity. For the carbonyl-ene reaction between ethyl trifluoropyruvate and alkenes, the Pd(II)-BINAPHANE catalyst afforded both good yields and extremely high enantioselectivities with *ee*s as high as 99.6%. A comparative study on the Pd(II) catalysts of the four C_2-bridged chiral diphosphines revealed that Pd(II)-BINAPHANE afforded the best enantioselectivity. The *ee* values derived from Pd(II)-BINAPHANE are much higher than those derived from the other three Pd(II) catalysts. A comparison of the catalyst structures shows that the Pd(II)-BINAPHANE catalyst is the only one that has two bulky (*R*)-binaphthyl groups close to the reaction site. Hence it creates a deep chiral space that can efficiently control the reaction behavior in the carbonyl-ene reactions resulting in excellent enantioselectivity.

Keywords: asymmetric catalysis; carbonyl-ene reaction; C–C bond formation; diphosphines; palladium

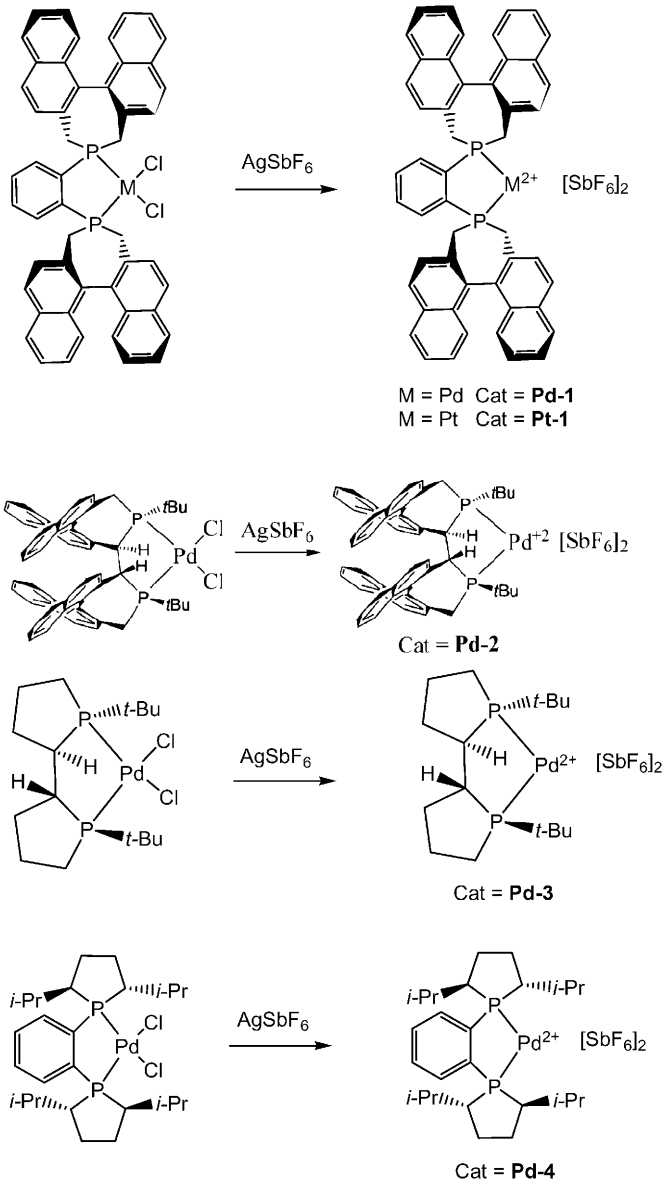
Introduction

An investigation of the correlation between catalyst structure and enantioselectivity is one of the key issues in fundamental asymmetric catalysis. For this reason, the concept of chiral space has been proposed to understand and guide the design of new chiral catalysts including both molecular chiral catalysts and heterogeneous chiral catalysts.[1] The chiral space can be reshaped by modifying the chiral ligands or chiral modifiers in order to achieve high enantioselectivity for a specific asymmetric reaction. Among the different strategies to make chiral catalysts studied so far, the use of conformationally restricted chiral ligands is still dominating this research area, because this kind of chiral catalysts is stable and generally cannot be racemized under the reaction conditions.

The chiral Lewis acid-catalyzed enantioselective carbonyl-ene reaction continue to attract much attention in asymmetric synthesis because it is an atom-economical tool to synthesize optically active homoallylic alcohols that are important building blocks in organic synthesis, especially for use in the pharmaceutical industry. Among the various chiral Lewis acid catalysts studied so far,[2–10] palladium(II) and platinum(II) complexes of C_4-bridged chiral diphosphines, such as *atropos*-BINAP {BINAP = 1,1′-[1,1′-binaphthalene]-2,2′-diylbis[1,1-diphenylphosphine]}, *atropos*-BIPHEP {BIPHEP = 1,1′-[[1,1′-biphenyl]-2,2′-diyl]-bis[1,1-diphenylphosphine]} and *atropos*-SEGPHOS-

type {SEGPHOS = 1,1′-[4,4′-bi-1,3-benzodioxole]-5,5′-diylbis[1,1-diphenylphosphine]} ligands, have been investigated for the enantioselective carbonyl-ene reactions. For example, Mikami[7a] and co-workers reported that {$Pd(CH_3CN)_2$[(*S*)-Tol-BINAP]} $(SbF_6)_2$ {(*S*)-Tol-BINAP = 1,1′-(1*S*)-[1,1′-binaphthalene]-2,2′-diyl-bis[1,1-bis(4-methylphenyl)phosphine]} was an efficient catalyst for the reaction between ethyl glyoxylate and methylenecyclohexane affording 88% yield and 78% *ee* at room temperature. Gagné[7b] and co-workers showed that {[(*S*)-MeO-BIPHEP]Pt}$(X)_2$ (X = OTf^-, SbF_6^-) {(*S*)-MeO-BIPHEP = 1,1′-[(1*S*)-6,6′-dimethoxy[1,1′-biphenyl]-2,2′-diyl]bis[1,1-diphenylphosphine]} afforded *ee* values up to 85% for the same carbonyl-ene reaction. Mikami[7c–e] and co-workers also reported that a "naked" palladium(II) complex with the chiral *atropos*-SEGPHOS and an *atropos*-platinum complex with BIPHEP are efficient catalysts for the carbonyl-ene reactions of ethyl trifluoropyruvate and alkenes affording *ee* values between 84% and 98%. Later, the Pd(II)-BINAP catalyzed enantioselective carbonyl-ene reactions between various aryglyoxals and alkenes were investigated by us affording good to excellent enantioselectivity with *ee* values as high as 93%.[7f]

Besides C_4-bridged chiral diphosphines, C_2-bridged chiral diphosphines are another class of privileged ligands that have been used in asymmetric reactions affording good to excellent enantioselectivity, such as asymmetric cyclization and asymmetric hydrogenation.[11] One advantage of C_2-bridged chiral diphosphines is that they form a stable five-membered chelate ring with the metal, thus providing a robust catalyst. Another advantage is that each of the two phosphorus atoms is attached to a chiral centre. These two chiral centres create a chiral space which can be reshaped by modifying the chiral centre's shape and size. Hence this provides us an opportunity to investigate the correlation between catalyst structure and enantioselectivity. Here we investigate the palladium(II) complexes of four C_2-bridged chiral diphosphines (see Scheme 1) for the enantioselective carbonyl-ene reactions. The employed four ligands are (*R*)-BINAPHANE {(11b*R*,11′b*R*)-4,4′-(1,2-phenylene)bis[4,5-dihydro-3*H*-dinaphtho[2,1-*c*:1′,2′-*e*]phosphepin]}, (*S*)-BINAPINE {(3*R*,3′*R*,4*S*,4′*S*,11b*S*,11′b*S*)-4,4′-bis(1,1-dimethylethyl)-4,4′,5,5′-tetrahydro-3,3′-bi-3*H*-dinaphtho[2,1-*c*:1′,2′-*e*]phosphepin}, (*S,S,R,R*)-TANGPHOS {(1*S*,1′*S*,2*R*,2′*R*)-1,1′-bis(1,1-dimethylethyl)-2,2′-biphospholane} and (*R,R*)-*i*-Pr-DUPHOS {(2*R*,2′*R*,5*R*,5′*R*)-1,1′-(1,2-phenylene)bis[2,5-bis(1-methylethyl)phospholane]}. The correlation between chiral space and enantioselectivity is discussed.



Scheme 1. Pd(II) group catalysts of C_2-bridged chiral diphosphines.

Results and Discussion

Comparison of Palladium(II) Complexes of C_2-Bridged Chiral Diphosphines

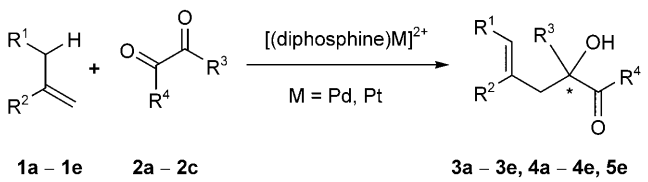
The four palladium(II) complexes of C_2-bridged chiral diphosphines are shown in Scheme 1. One common feature of these complexes is that they contain a stable five-membered chelate ring. Each chiral diphosphine ligand has a pair of chiral centres that are different in shape and size for different ligands, thus creating different chiral spaces. The Pd-(*R*)-BINAPHANE (**Pd-1**) has two bulky (*R*)-binaphthyl groups close to the reaction site, hence it creates a deep chiral space with the reaction site inside.[11a] The

Pd-(*S*)-BINAPINE (**Pd-2**) also has two bulky (*R*)-binaphthyl groups, however they are relatively far away from the reaction site, and cannot significantly affect the asymmetric reaction. Therefore the chiral space of **Pd-2** is mainly created by the two *tert*-butyl groups which are much smaller than the (*R*)-binaphthyl group, hence **Pd-2** has a relatively smaller chiral space for asymmetric reaction. Both Pd-(*S,S,R,R*)-TANGPHOS (**Pd-3**) and Pd-(*R,R*)-*iPr*-DUPHOS (**Pd-4**) cannot create chiral spaces as deep as that of **Pd-1** because the chiral centres of **Pd-3** and **Pd-4** are smaller than those of **Pd-1**. Therefore in comparison, **Pd-1** is the only catalyst that provides a deep chiral space for asymmetric reaction.

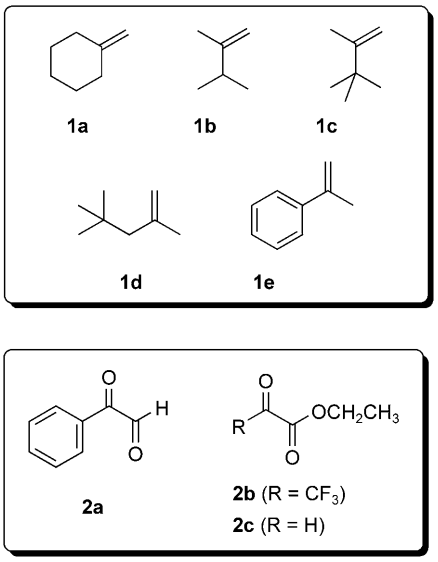
A catalytic mechanism has been proposed to interpret the palladium(II)-catalyzed enantioselective carbonyl-ene reactions.[7] In the catalytic cycle, the dicarbonyl compound is first activated by coordination to the palladium to form an intermediate. This key intermediate will be attacked by an alkene to initiate the carbonyl-ene reaction. Therefore the catalyst should have a chiral space that is deep enough to affect both of the substrates, so that the reaction behavior can be well controlled to achieve high enantioselectivity. This may indicate that **Pd-1** with a deep chiral space can display high enantioselectivity for the carbonyl-ene reaction.

Enantioselective Carbonyl-Ene Reactions of Phenylglyoxal with Alkenes

All the chiral Pd(II) and Pt(II) catalysts shown in Scheme 1 were investigated for the enantioselective carbonyl-ene reactions of phenylglyoxal (**2a**) with five alkenes including methylenecyclohexane (**1a**), 2,3-dimethyl-1-butene (**1b**), 2,3,3-trimethyl-1-butene (**1c**), 2,4,4-trimethyl-1-pentene (**1d**) and α-methylstyrene (**1e**) (see Scheme 2 and Scheme 3). In order to make the enantioseletive carbonyl-ene reactions more practical, here we used equimolar amounts of carbonyl compound and alkene to run the reaction. Hence the isolated yields are more useful compared to those derived from the reactions using a large excess of carbonyl compound. For the phenylglyoxal-based reactions, with the prolongation of reaction time, the color of the reaction mixture became darker and darker. TLC and flash chromatography showed that a



Scheme 2. Enantioselective carbonyl-ene reactions.



Scheme 3. Substrates employed in the enantioselective carbonyl-ene reactions.

long reaction time usually resulted in the formation of some impurities. The impurities are increasing with the reaction time and finally resulting in decreased yield. For example, for the **Pd-1**-catalyzed reaction of phenylglyoxal with **1b**, **1c** or **1d**, the color changed from light orange yellow to dark green or greenish brown. After 16 h of an overnight run, TLC indicated that the impurities were clear and strong, but the product became very weak. Flash chromatography afforded only a trace of impurities. In comparison, a 2 h run can afford a clean product albeit in low yields (14%, 29% and 39% yields for **1b–1d**, entries 3–5, Table 1). Hence the reactions were usually run for a short time of maximally 2 h in this study, in order to obtain a cleaner product and/or a better yield.

The results show that **Pd-1** displayed good to excellent enantioselectivity with *ee* values of 81.1%, 90.2%, 99.0%, 89.0% and 87.1% for alkenes **1a**–**1e** (see entries 1, 3–6, Table 1). However, compared to **Pd-1**, **Pd-2** displayed much lower enantioselectivity with *ee* values of 26.7%, 61.3%, 60.1%, 61.1% and 50.8% for alkenes **1a**–**1e** (see entries 12–16, Table 1). **Pd-3** displayed moderate to good enantioselectivity with *ee* values of 41.7%, 80.2%, 83.5%, 84.0% and 77.3% for alkenes **1a**–**1e** (see entries 17–21, Table 1). However these *ee* values are still much lower than those of **Pd-1. Pd-4** displayed very low enantioselectivity with *ee* values of 29.6%, 28.0%, 29.0%, 32.2% and 39.3% for alkenes **1a**–**1e** (see entries 22–26, Table 1). These results are consistent with the structural analysis. **Pd-1** with a deep chiral space displayed the best enantioselectivity among the four Pd(II) complexes of C_2-bridged chiral diphosphine ligands.

Pt(II)-(*R*)-BINAPHANE (**Pt-1**) was also investigated for the enantioselective carbonyl-ene reactions of

Table 1. Enantioselective carbonyl-ene reactions of phenylglyoxal with alkenes.[a]

Entry	Catalyst	Alkene	Product	Time [h]	Yield[b] [%]	*ee*[c] [%]
1	**Pd-1**	**1a**	**3a**	2	25	81.1 (*R*)
2[d]	**Pd-1**	**1a**	**3a**	1	27	81.4 (*R*)
3	**Pd-1**	**1b**	**3b**	2	14	90.2 (*R*)
4	**Pd-1**	**1c**	**3c**	2	29	99.0 (*R*)
5	**Pd-1**	**1d**	**3d**	2	39	89.0 (*R*)
6[d]	**Pd-1**	**1e**	**3e**	1	26	87.1 (*R*)
7	**Pt-1**	**1a**	**3a**	2	64	84.9 (*R*)
8	**Pt-1**	**1b**	**3b**	2	58	90.8 (*R*)
9	**Pt-1**	**1c**	**3c**	2	44	91.0 (*R*)
10	**Pt-1**	**1d**	**3d**	2	58	78.2 (*R*)
11	**Pt-1**	**1e**	**3e**	2	42	79.3 (*R*)
12[d]	**Pd-2**	**1a**	**3a**	1	10	26.7 (*S*)
13	**Pd-2**	**1b**	**3b**	2	30	61.3 (*S*)
14	**Pd-2**	**1c**	**3c**	2	39	60.1 (*S*)
15	**Pd-2**	**1d**	**3d**	2	42	61.1 (*S*)
16[d]	**Pd-2**	**1e**	**3e**	1	14	50.8 (*S*)
17[d]	**Pd-3**	**1a**	**3a**	1	14	41.7 (*S*)
18	**Pd-3**	**1b**	**3b**	2	29	80.2 (*S*)
19	**Pd-3**	**1c**	**3c**	2	25	83.5 (*S*)
20	**Pd-3**	**1d**	**3d**	2	40	84.0 (*S*)
21[d]	**Pd-3**	**1e**	**3e**	1	16	77.3 (*S*)
22[d]	**Pd-4**	**1a**	**3a**	1	21	29.6 (*R*)
23	**Pd-4**	**1b**	**3b**	2	13	28.0 (*R*)
24	**Pd-4**	**1c**	**3c**	2	13	29.0 (*R*)
25	**Pd-4**	**1d**	**3d**	2	32	32.2 (*R*)
26[d]	**Pd-4**	**1e**	**3e**	1	25	39.3 (*R*)

[a] *Reaction conditions:* All the reactions were run at room temperature. Pd(II) or Pt(II) catalyst, 0.0125 mmol (5 mol%); solution of phenylglyoxal in dichloromethane (0.25 M), 1 mL; alkene, 0.25 mmol.

[b] Isolated yield with flash chromatography.

[c] Determined by HPLC with a Chiralcel OD-H column for products **3a**–**3d**, with a Chiralcel OB-H column for product **3e**. The absolute configurations of the carbonyl-ene products (**3a**–**3e**) were determined by comparing the HPLC retention times with those reported in the literature, or by comparison with analogous products reported in the literature.

[d] Using 0.25 mmol phenylglyoxal monohydrate instead of 1 mL solution of phenylglyoxal in dichloromethane.

phenylglyoxal with the five alkenes (see entries 7–11, Table 1). Compared to its palladium counterpart, **Pt-1** afforded higher isolated yields under identical conditions (**Pt-1**: 42%–64% yields *vs* **Pd-1**: 14%–39% yields, see entries 1–11, Table 1). However, **Pt-1** displayed lower enantioselectivity for the reactions of phenylglyoxal with alkenes **1c**–**1e** (**Pt-1**: 91.0%, 78.2%, 79.3% *vs.* **Pd-1**: 99.0%, 89.0%, 87.1%), albeit **Pt-1** displayed a slightly higher enantioselectivity for the reactions of phenylglyoxal with alkenes **1a** and **1b** (**Pt-1**: 84.9%, 90.8% *vs.* **Pd-1**: 81.1%, 90.2%).

Enantioselective Carbonyl-Ene Reactions of 2b and 2c with Alkenes

Because **Pd-1** is a highly enantioselective catalyst, it was also investigated for the carbonyl-ene reactions of ethyl trifluoropyruvate with the five alkenes (see Scheme 2 and Scheme 3). Compared to the phenylglyoxal-based reactions with low yields (14%–39%), ethyl trifluoropyruvate-based reactions afforded significantly improved yields (60%–78%, Table 2) because ethyl trifluoropyruvate is a more active substrate compared to phenylglyoxal. More importantly, all the ethyl trifluoropyruvate-based reactions afforded excellent enantioselectivity with *ee* values of 99.4%, 99.3%, 99.6%, 98.8% and 91.2% for alkenes **1a**–**1e**. In comparison, these *ee* values are much higher or comparable relative to the corresponding phenylglyoxal-based reactions. It should be noted that alkene **1b** afforded only one product **3b** when reacted with phenylglyoxal. However it afforded two products (**4b**:**4b′** = 2.5:1 calculated from ^{1}H NMR) when reacted with ethyl trifluoropyruvate, and both of the products have extremely high *ee* values (99.3% and 99.6% for **4b** and **4b′**).

Further studies showed that **Pd-1** and **Pt-1** can also catalyze the reaction of ethyl glyoxylate and α-methylstyrene affording good enantioselectivities (see entries 6 and 7, Table 2). For a 2 h run at room temperature, **Pd-1** displayed a higher *ee* value, but a lower yield (86.8% *ee*, 38% yield) compared to **Pt-1** (70.6% *ee*, 46% yield). The results in Table 1 and Table 2 show that **Pd-1** is versatile to catalyze the enantioselective carbonyl-ene reactions between different kinds of carbonyl compounds and alkenes.

Mechanistic Considerations for the Formation of 4b and 4b′

Among the five alkenes shown in Scheme 3, 2,3-dimethyl-1-butene (**1b**) is the smallest molecule, while ethyl trifluoropyruvate is also smaller than phenylglyoxal. Hence when considering the catalytic mechanism,[7] the chiral catalyst (**Pd-1**) may still have sufficient space to allow **1b** to approach the coordinated ethyl trifluoropyruvate in two ways (see paths **A** and **B**, Scheme 4) producing two products **4b** and **4b′**. Because of its lower steric hindrance, path **A** still dominates the catalytic cycle to afford the major product **4b** in a ratio of **4b**:**4b′** = 2.5:1.

The Water Tolerance of Pd-1

When the solid compound **Pd-1** or even its CD_2Cl_2 solution was exposed in the air for one day, its ^{31}P NMR had no shift, indicating an air-stable compound. For

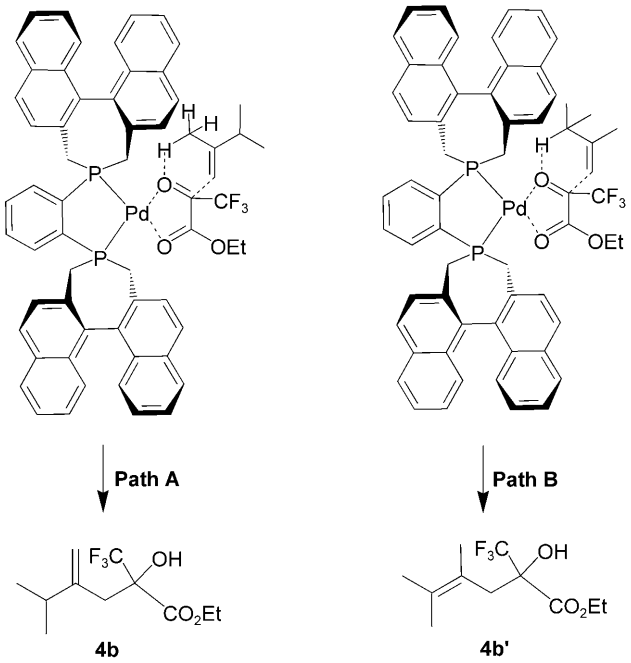
Table 2. Enantioselective carbonyl-ene reactions of **2b** and **2c** with alkenes.[a]

Entry	Catalyst	Alkene	Carbonyl compound	Product	Time [h]	Yield[b] [%]	*ee*[c] [%]
1	**Pd-1**	**1a**	**2b**	**4a**	1	78	99.4
2	**Pd-1**	**1b**	**2b**	**4b**	1	60 (**4b**:**24′** = 2.5)	99.3
				4b′			99.6
3	**Pd-1**	**1c**	**2b**	**4c**	1	64	99.6
4	**Pd-1**	**1d**	**2b**	**4d**	1	76	98.8
5	**Pd-1**	**1e**	**2b**	**4e**	2	64	91.2
6	**Pd-1**	**1e**	**2c**	**5e**	2	38	86.8
7	**Pt-1**	**1e**	**2c**	**5e**	2	46	70.6

[a] *Reaction conditions:* All the reactions were run at room temperature. **Pd-1** or **Pt-1** catalyst, 0.0125 mmol (5 mol%); alkene, 0.25 mmol; for entries 1–5, 0.25 mmol ethyl trifluoropyruvate was used; For entries 6–7, 0.5 mmol ethyl glyoxylate (50% solution in toluene) was used.

[b] Isolated yield with flash chromatography.

[c] Determined by GC with a Varian CP7502 chiral column (cp-Chirasil-dexB capillary 25.0 m × 250 μm × 0.25 μm nominal) for products **4a–4d**, by HPLC with a Chiralpak AS-H column for product **4e** and **5e**.



Scheme 4. The mechanism of forming two products.

the 1 h reaction of phenylglyoxal monohydrate and methylenecyclohexane, **Pd-1** gave 27% yield and 81.4% *ee* (entry 2, Table 1) which is comparable to the *ee* value using dehydrated phenylglyoxal (81.1% *ee*, entry 1, Table 1). Therefore, **Pd-1** is tolerant to traces of water present in the reaction.

Conclusions

We have investigated the palladium(II) complexes of four C_2-bridged chiral diphosphines as catalysts for the enantioselective carbonyl-ene reactions. Pd-BINAPHANE was demonstrated to be a highly enantioselective catalyst for both the phenylglyoxal-based reactions and ethyl trifluoropyruvate-based reactions with *ee* values as high as 99.6%. Pt(II)-BINAPHANE also afforded satisfactory enantioselectivity with improved yields as compared to its Pd(II) counterpart. However, the other three Pd(II) catalysts of (*S*)-BINAPINE, (*S,S,R,R*)-TANGPHOS and (*R,R*)-*i*-Pr-DUPHOS afforded much lower *ee* values compared to Pd-BINAPHANE. A comparison of catalyst structure reveals that Pd(II)-BINAPHANE is the only catalyst that has two bulky (*R*)-binaphthyl groups close to the reaction site. Hence it creates a deeper chiral space relative to the other three chiral palladium(II) catalysts. The deep chiral space of Pd-BINAPHANE may efficiently control the reaction behavior of the two substrates resulting in excellent enantioselectivities.

Experimental Section

General Considerations

All manipulations were carried out under an atmosphere of nitrogen or argon using standard Schlenk line techniques. ^{1}H NMR, ^{13}C NMR and ^{19}F NMR were recorded in $CDCl_3$ or CD_2Cl_2 on a Bruker 400 spectrometer. ^{19}F NMR data were measured against (trifluoromethyl)benzene ($\delta = -62.9$ ppm). Analytical high-performance liquid chromatography (HPLC) was performed on an Agilent 110 Series HPLC system equipped with a UV detector using a chiral column selected from Chiralcel OD-H, Chiralcel OB-H and Chiralpak AS-H columns. Chiral GC analysis was performed on an Agilent 6890N Network GC system using a Varian CP7502 chiral column (cp-Chirasil-dexB capillary 25.0 m × 250 μm × 0.25 μm nominal). Elemental analysis was performed on a EuroEA3000 Series Elemental Analyzer. High resolution mass spectra were obtained on an Agilent LC-MS TOF. Purification of reaction products was carried out by flash column chromatography on silica gel. Phenylglyoxal monohydrate was purchased from Sigma–Aldrich,

dried under vacuum at 90 °C and used as a 0.25 M dichloromethane solution. Ethyl trifluoropyruvate was purchased from Alfa Aesar and used without pretreatment. Ethyl glyoxylate (50% in toluene) was purchased from Sigma-Alpha. All the alkenes including methylenecyclohexane, 2,3-dimethyl-1-butene, 2,3,3-trimethyl-1-butene, 2,4,4-trimethyl-1-pentene and α-methylstyrene were purchased from Sigma–Aldrich and used without pretreatment. (*R*)-BINAPHANE, (*S*)-BINAPINE, (*S,S,R,R*)-TANGPHOS and (*R,R*)-*i*-Pr-DUPHOS were purchased from STREM. [(*R,R*)-*i*-Pr-DUPHOS]$PdCl_2$ was synthesized by the reaction of (COD)$PdCl_2$ with (*R,R*)-*i*-Pr-DUPHOS following the reported method.[12] Instead of the synthetic procedure by treatment of $(CH_3CN)_2PdCl_2$ with (*R*)-BINAPHANE,[11a] here [(*R*)-BINAPHANE]$PdCl_2$ was also synthesized by the reaction of (COD)$PdCl_2$ with (*R*)-BINAPHANE. The racemic carbonyl-ene products were prepared with $(Ph_3P)_2PdCl_2$.

General Procedure for the Synthesis of Chiral Palladium Group Complexes

In a 50-mL Schlenk tube, a desired amount of (COD)$PdCl_2$ or (COD)$PtCl_2$ was dissolved in dichloromethane (10 mL), to which a solution of an equimolar amount of the chiral diphosphine in dichloromethane (10 mL) was added dropwise under vigorous stirring. The resulting solution was stirred overnight at room temperature, then dichloromethane was removed under vacuum affording a yellow powder for the Pd(II) complex or a white powder for Pt(II) complex. The obtained crude product was washed with ether (10 mL × 2) and dried under vacuum.

[(*R*)-BINAPHANE]$PdCl_2$

(*R*)-BINAPHANE (250 mg, 0.36 mmol) and an equimolar amount of (COD)$PdCl_2$ were used to synthesize the title catalyst. The obtained crude product was dissolved in dichloromethane (10 mL) and layered with pentane (15 mL) at room temperature. The obtained pale yellow solid was washed with pentane (10 mL) and dried under vacuum affording 172 mg of the product. The solution mixture was dried giving a residue that was dissolved in dichloromethane (5 mL) and layered with pentane (10 mL) affording a second batch of the product (64 mg). Total yield: 75%. $^{31}P\{^1H\}$ NMR (CD_2Cl_2, 162 MHz): δ = 84.2 (s); $^1H\{^{31}P\}$ NMR (CD_2Cl_2, 400 MHz): δ = 3.30 (d, C*H*$_2$, 2H, *J* = 14.7 Hz), 3.65 (d, C*H*$_2$, 2H, *J* = 14.2 Hz), 3.87 (d, C*H*$_2$, 2H, *J* = 14.3 Hz), 4.43 (d, C*H*$_2$, 2H, *J* = 14.6 Hz), 6.43–6.45 (q, Ar-*H*, 2H, *J* = 3.2 Hz), 7.08 (d, Ar-*H*, 2H, *J* = 8.5 Hz), 7.18 (d, Ar-*H*, 2H, *J* = 8.4 Hz), 7.22–7.27 (m, Ar-*H*, 4H), 7.31–7.38 (m, Ar-*H*, 4H), 7.50–7.60 (m, Ar-*H*, 4H), 7.84 (d, Ar-*H*, 2H, *J* = 8.5 Hz), 7.99–8.08 (m, Ar-*H*, 8H); $^{13}C\{^1H\}\{^{31}P\}$ NMR (CD_2Cl_2, 100 MHz): δ = 34.47, 34.60, 125.74, 125.90, 126.17, 126.59, 126.65, 127.18, 128.16, 128.34, 128.37, 128.58, 128.94, 130.04, 130.37, 131.06, 132.26, 132.49, 132.77, 132.97, 133.26, 133.29, 133.60, 134.55, 139.50; anal. calcd. for $C_{50}H_{36}Cl_2P_2Pd$ (876.09): C 68.55%, H 4.14%; found: C 68.32%, H 4.40%.

[(*R*)-BINAPHANE]$PtCl_2$

(*R*)-BINAPHANE (250 mg, 0.36 mmol) and an equimolar amount of (COD)$PtCl_2$ were used to synthesize the title catalyst. The crude product was dissolved in dichloromethane (5 mL) and layered with diethyl ether (15 mL) at room temperature. The obtained white solid was washed with pentane (10 mL) and dried under vacuum affording 199 mg of the product. The solution mixture was dried giving a residue that was dissolved in dichloromethane (2 mL) and layered with diethyl ether (10 mL) affording a second batch of the product (38 mg). Total yield: 69%. $^{31}P\{^1H\}$ NMR (CD_2Cl_2, 162 MHz): δ = 59.2 (t, $J_{Pt,P}$ = 1737 Hz); $^1H\{^{31}P\}$ NMR (CD_2Cl_2, 400 MHz): δ = 3.12 (dd, C*H*$_2$, 2H, *J* = 14.7 Hz, *J* = 5.6 Hz), 3.64 (dd, C*H*$_2$, 2H, *J* = 14.1 Hz, *J* = 5.6 Hz), 3.80 (t, C*H*$_2$, 2H, *J* = 14.9 Hz), 4.25 (t, C*H*$_2$, 2H, *J* = 14.5 Hz), 6.40–6.44 (m, Ar-*H*, 2H), 6.97 (d, Ar-*H*, 2H, *J* = 8.5 Hz), 7.09–7.13 (m, Ar-*H*, 6H), 7.18–7.22 (m, Ar-*H*, 4H), 7.39 (t, Ar-*H*, 2H, *J* = 7.5 Hz), 7.44 (t, Ar-*H*, 2H, *J* = 7.5 Hz), 7.68 (d, Ar-*H*, 2H, *J* = 8.4 Hz), 7.89–7.95 (m, Ar-*H*, 8H); $^{13}C\{^1H\}\{^{31}P\}$ NMR (CD_2Cl_2, 100 MHz): δ = 33.28, 34.14, 125.68, 125.89, 126.09, 126.53, 126.67, 127.17, 128.19, 128.34, 128.35, 128.59, 128.91, 130.00, 130.09, 130.90, 132.02, 132.31, 132.65, 132.72, 133.24, 133.45, 134.48, 139.63; anal. calcd. for $C_{50}H_{36}Cl_2P_2Pt$ (964.75): C 62.25%, H 3.76%; found: C 62.09%, H 4.21%.

[(*S*)-BINAPINE]$PdCl_2$

(*S*)-BINAPINE (500 mg, 0.68 mmol) and an equimolar amount of (COD)$PdCl_2$ were used to synthesize the title catalyst. The obtained crude product was dissolved in dichloromethane (10 mL), layered with pentane (15 mL) and stored in a freezer (~ −20 °C). The obtained pale yellow solid was washed with pentane (5 mL) and dried under vacuum affording 198 mg of the product. The solution mixture was dried giving a residue that was dissolved in dichloromethane (6 mL), layered with pentane (10 mL) and stored in a freezer affording a second batch of the product (189 mg). Total yield: 62%. $^{31}P\{^1H\}$ NMR (CD_2Cl_2, 162 MHz): δ = 119.1 (s); $^1H\{^{31}P\}$ NMR (CD_2Cl_2, 400 MHz): δ = 0.55 (s, C*H*$_3$, 18H), 2.95 (d, C*H*$_2$, 2H, *J* = 13.2 Hz), 3.45 (s, C*H*, 2H), 3.79 (d, C*H*$_2$, 2H, *J* = 13.2 Hz), 6.69 (d, Ar-*H*, 2H, *J* = 8.5 Hz), 6.95 (d, Ar-*H*, 2H, *J* = 8.6 Hz), 7.16–7.20 (m, Ar-*H*, 2H), 7.29 (d, Ar-*H*, 2H, *J* = 8.4 Hz), 7.43–7.47 (m, Ar-*H*, 2H), 7.50–7.55 (m, Ar-*H*, 2H), 7.60–7.64 (m, Ar-*H*, 4H), 7.84 (d, Ar-*H*, 2H, *J* = 8.1 Hz), 7.89 (d, Ar-*H*, 2H, *J* = 8.4 Hz), 8.08 (d, Ar-*H*, 4H, *J* = 8.4 Hz); $^{13}C\{^1H\}\{^{31}P\}$ NMR (CD_2Cl_2, 100 MHz): δ = 27.90, 28.52, 37.34, 53.07, 126.23, 126.28, 126.40, 126.43, 126.82, 127.09, 127.99, 128.45, 129.13, 129.39, 130.17, 130.34, 130.87, 132.66, 132.99, 133.04, 133.39, 133.46, 133.72, 135.16; anal. calcd. for $C_{52}H_{48}Cl_2P_2Pd$ (912.21): C 68.47%, H 5.30%; found: C 68.19%, H 5.50%.

[(*S,S,R,R*)-TANGPHOS]$PdCl_2$

(*S,S,R,R*)-TANGPHOS (250 mg, 0.87 mmol) and an equimolar amount of (COD)$PdCl_2$ were used to synthesize the title catalyst. The crude product was dissolved in dichloromethane (10 mL), layered with ether (10 mL) and stored in a freezer (~ −20 °C). The obtained pale yellow solid was washed with pentane (5 mL) and dried under vacuum affording 105 mg of the product. The solution mixture was dried giving a residue that was dissolved in dichloromethane (5 mL), layered with diethyl ether (10 mL) and stored in a freezer affording a second batch of the product (98 mg). Total yield: 50%. $^{31}P\{^1H\}$ NMR (CD_2Cl_2, 162 MHz): δ =

121.6 (s); $^{1}H\{^{31}P\}$ NMR (CD_2Cl_2, 400 MHz): δ = 1.43 (s, CH_3, 18H), 1.59–1.76 (m, CH_2, 4H), 2.11–2.16 (m, CH_2, 2H), 2.29–2.35 (m, CH_2, 2H), 2.45–2.49 (m, CH_2, 4H), 2.63–2.68 (m, CH, 2H); $^{13}C\{^{1}H\}\{^{31}P\}$ NMR (CD_2Cl_2, 100 MHz): δ = 26.65, 27.00, 29.26, 34.70, 35.68, 45.85; anal. calcd. for $C_{16}H_{32}Cl_2P_2Pd$ (463.70): C 41.44%, H 6.96%; found: C 41.20%, H 6.78%.

General Procedure for Catalyst Activation

A small Schlenk tube was charged with 0.0125 mmol of the desired [chiral diphosphine]MCl_2 (M = Pd, Pt) and $AgSbF_6$ (2.5 equivalents), followed by the addition of dichloromethane (1 mL). The resulting mixture was stirred for 30 min under a nitrogen or argon atmosphere at room temperature, giving the *in situ* activated catalyst solution of {[chiral diphosphine]M}$(SbF_6)_2$ (M = Pd, Pt).

General Procedure for Enantioselective Carbonyl-Ene Reactions

To a solution of the *in situ* prepared catalyst in dichloromethane according to the above described activation method, was added a dichloromethane solution of phenylglyoxal (1 mL, 0.25 mmol/mL) or 0.25 mmol ethyl trifluoropyruvate or 0.5 mmol ethyl glyoxylate (50% in toluene), followed by 0.25 mmol of the desired alkene. The resulting mixture was stirred for 1 or 2 h at room temperature. Then the reaction mixture was concentrated under vacuum and diluted with hexane (1.5 mL). The mixture was immediately loaded onto silica gel, and eluted with a hexane/ethyl acetate mixture to give the corresponding compound. The isolated product was characterized with ^{1}H NMR, ^{13}C NMR and ^{19}F NMR spectrosocopy. The enantiomeric excess was determined by HPLC or GC with a chiral column.

The following details for the synthesis and analysis of compounds **3a**–**3e** and **4a**–**4e** were obtained using **Pd-1** as the catalyst.

3-(1-Cyclohexenyl)-2-hydroxy-1-phenyl-1-propanone (3a)

The title compound was prepared according to the general procedure using 0.25 mmol of phenylglyoxal and 0.25 mmol of methylenecyclohexane. The pure product was obtained by column chromatography over silica gel eluted with hexane/ethyl acetate (9:1). The ^{1}H NMR and ^{13}C NMR of the product were consistent with the reported data.[6a]. The enantiomeric excess was determined by HPLC with a Chiralcel OD-H column [1.0% 2-propanol in hexane, flow 1.0 mL min^{-1}, (*S*)-enantiomer R_t = 13.2 min (minor), (*R*)-enantiomer R_t = 20.12 min (major)].

2-Hydroxy-5-methyl-4-methylene-1-phenyl-1-hexanone (3b)

The title compound was prepared according to the general procedure using 0.25 mmol of phenylglyoxal and 0.25 mmol of 2,3-dimethyl-1-butene. The pure product was obtained by column chromatography over silica gel eluted with hexane/ethyl acetate (9:1). The ^{1}H NMR and ^{13}C NMR of the product were consistent with the reported data.[6a] The enantiomeric excess was determined by HPLC with a Chiralcel OD-H column [0.8% 2-propanol in hexane, flow 0.5 mL min^{-1}, (*S*)-enantiomer R_t = 27.5 min(minor), (*R*)-enantiomer R_t = 58.6 min(major)].

2-Hydroxy-5,5-dimethyl-4-methylene-1-phenyl-1-hexanone (3c)

The title compound was prepared according to the general procedure using 0.25 mmol of phenylglyoxal and 0.25 mmol of 2,3,3-trimethyl-1-butene. The pure product was obtained by column chromatography over silica gel eluted with hexane/ethyl acetate (9:1). ^{1}H NMR ($CDCl_3$, 400 MHz): δ = 0.97 [s, $C(CH_3)_3$, 9H], 2.09 [dd, $CH_2C(OH)$, 1H, J = 16.3 Hz, J = 9.7 Hz], 2.52 [dt, -$CH_2C(OH)$, 1H, J = 16.5 Hz, J = 1.0 Hz], 3.61 (s, broad, OH, 1H), 5.05 (s, C=CH_2, 1H), 5.06 (s, C=CH_2, 1H), 5.21 [dd,-$CH(OH)$, 1H, J = 9.7 Hz, J = 1.9 Hz], 7.42–7.46 (m, Ar-H, 2H), 7.53–7.57 (m, Ar-H, 1H), 7.85–7.88 (m, Ar-H, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 29.06, 36.16, 37.33, 72.48, 108.36, 128.62, 128.91, 133.63, 134.02, 153.19, 202.03. The enantiomeric excess was determined by HPLC with a Chiralcel OD-H column [1.0% 2-propanol in hexane, flow 1.0 mL min^{-1}, (*S*)-enantiomer R_t = 7.9 min (minor), (*R*)-enantiomer R_t = 11.7 min (major)].

2-Hydroxy-6,6-dimethyl-4-methylene-1-phenyl-1-heptanone (3d)

The title compound was prepared according to the general procedure using 0.25 mmol of phenylglyoxal and 0.25 mmol of 2,4,4-trimethyl-1-pentene. The pure product was obtained by column chromatography over silica gel eluted with hexane/ethyl acetate (9:1). The ^{1}H NMR and ^{13}C NMR of the product were consistent with the reported data.[6a] The enantiomeric excess was determined by HPLC with a Chiralcel OD-H column [1.0% 2-propanol in hexane, flow 1.0 mL min^{-1}, (*S*)-enantiomer R_t = 10.2 min (minor), (*R*)-enantiomer R_t = 14.3 min (major)].

2-Hydroxy-1,4-diphenyl-4-penten-1-one (3e)

The title compound was prepared according to the general procedure using 0.25 mmol of phenylglyoxal and 0.25 mmol of α-methylsyrene. The pure product was obtained by column chromatography over silica gel eluted with hexane/ethyl acetate (9:1). The ^{1}H NMR and ^{13}C NMR of the product were consistent with the reported data.[7e] The enantiomeric excess was determined by HPLC with a Chiralcel OB-H column [3.0% 2-propanol in hexane, flow 1.0 mL min^{-1}, (*R*)-enantiomer R_t = 20.5 min (major), (*S*)-enantiomer R_t = 27.4 min (minor)].

Ethyl 2-(Cyclohexenylmethyl)-3,3,3-trifluoro-2-hydroxypropanoate (4a)

The title compound was prepared according to the general procedure using 0.25 mmol of ethyl trifluoropyruvate and 0.25 mmol of methylenecyclohexane. The pure product was obtained by column chromatography over silica gel eluted with hexane/ethyl acetate (5:1). ^{1}H NMR ($CDCl_3$, 400 MHz): δ = 1.27 (t, CH_3, 3H, J = 7.2 Hz), 1.41–1.53 (m, CH_2CH_2, 4H), 1.75–2.05 (m, CH_2C=C, 4H), 2.43 [d, $CH_2C(OH)$, 1H, J = 13.9 Hz], 2.59 [d, CH_2-C(OH), 1H, J = 13.9 Hz], 3.72 (broad, OH, 1H), 4.20–4.32 (m, $COOCH_2$,

2H), 5.48 (s, -C=C*H*-, 1H]; ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 13.98, 21.93, 22.85, 25.40, 29.77, 39.60, 63.55, 78.22 (q, $J_{C,F}$ = 28.5 Hz), 123.38 (q, $J_{C,F}$ = 286.3 Hz), 127.69, 130.88, 169.73; ^{19}F{^{1}H} NMR ($CDCl_3$, 376 MHz) δ = −78.73; HR-MS (ESI): *m/z* = 289.1011, calcd. for $C_{12}H_{17}F_3O_3Na$ [M + Na]$^+$: 289.1022. The enantiomeric excess was determined by GC using a Varian CP7502 column [50 °C for 2 min; ramp to 110 °C at 10 °C min^{-1} and hold 30 min; then ramp to 180 °C at 10 °C min^{-1} and hold 20 min, gas flow: 1 mL min^{-1}); R_t of the major enantiomer = 23.4 min, R_t of the minor enantiomer = 25.5 min.

Ethyl 2-Hydroxy-5-methyl-4-methylene-2-(trifluoromethyl)-hexanoate (4b) and Ethyl 2-Hydroxy-4,5-dimethyl-2-(trifluoromethyl)-4-hexenoate(4b′)

The title compounds were prepared according to the general procedure using 0.25 mmol of ethyl trifluoropyruvate and 0.25 mmol of 2,3-dimethyl-1-butene. The products of two couples of enantiomers were obtained by column chromatography over silica gel eluted with hexane/ethyl acetate (15:1). ^{1}H NMR ($CDCl_3$, 400 MHz, mixture of **4b** and **4b′**): δ = 0.937 (d, CHC*H*$_3$ of **4b**, 3H, *J* = 6.8 Hz), 0.943 (d, CHC*H*$_3$ of **4b**, 3H, *J* = 6.8 Hz), 1.24–1.28 (m, CH_2CH_3 of **4b** and **4b′**), 1.57 (s, CH_3 of **4b′**, 3H), 1.59 (s, CH_3 of **4b′**, 3H), 1.62 (s, CH_3 of **4b′**, 3H), 2.22 [sept, C*H*(CH$_3$)$_2$ of **4b**, 1H, *J* = 6.8 Hz], 2.59, 2.67, 2.76 (d,d,d, C*H*$_2$ of **4b** and **4b′**, *J* = 14.5 Hz, *J* = 14.3 Hz, *J* = 14.1 Hz), 3.64 (s broad, O*H* of **4b′**, 1H), 3.79 (s broad, O*H* of **4b**, 1H), 4.12–4.36 (m, OC*H*$_2$ of **4b** and **4b′**), 4.80 (s, C=C*H*$_2$ of **4b**, 1H), 4.85 (s, C=C*H*$_2$ of **4b**, 1H). The ratio of **4b** to **4b′** calculated from ^{1}H NMR is 2.5. ^{13}C NMR ($CDCl_3$, 100 MHz, mixture of **4b** and **4b′**): data of **4b**: δ = 13.83, 21.37, 21.81, 34.11, 35.66, 63.62, 78.22 (q, $J_{C,F}$ = 28.4 Hz), 111.56, 123.37 (q, $J_{C,F}$ = 286.7 Hz), 148.95, 169.51; data of **4b′**: δ = 13.76, 19.38, 20.91, 20.97, 36.18, 63.50, (a group of small peaks are hidden in between the strong solvent peaks, its δ and *J* cannot be accurately calculated), 119.80, 123.60 (q, $J_{C,F}$ = 286.1 Hz), 131.58, 170.09; ^{19}F{^{1}H} NMR ($CDCl_3$, 376 MHz, mixture of **4b** and **4b′**): δ = −78.66 (**4b′**), −79.02 (**4b**); HR-MS (ESI): *m/z* = 277.1009, calcd. for $C_{11}H_{17}F_3O_3Na$ [M + Na]$^+$: 277.1022. The enantiomeric excess was determined by GC using a Varian CP7502 column (50 °C for 2 min; ramp to 110 °C at 10 °C min^{-1} and hold 20 min; then ramp to 180 °C at 10 °C min^{-1} and hold 5 min, gas flow: 1 mL min^{-1}): for product **4b**, R_t of the major enantiomer = 10.8 min, R_t of the minor enantiomer = 11.1 min; for product **4b′**, R_t of the major enantiomer = 12.6 min, R_t of the minor enantiomer = 13.1 min.

Ethyl 2-Hydroxy-5,5-dimethyl-4-methylene-2-(trifluoromethyl)-hexanoate (4c)

The title compound was prepared according to the general procedure using 0.25 mmol of ethyl trifluoropyruvate and 0.25 mmol of 2,3,3-trimethyl-1-butene. The pure product was obtained by column chromatography over silica gel eluted with hexane/ethyl acetate (15:1). ^{1}H NMR ($CDCl_3$, 400 MHz): δ = 1.06 [s, C(C*H*$_3$)$_3$, 9H], 1.30 (t, OCH$_2$C*H*$_3$, 3H, *J* = 7.2 Hz), 2.66 [dt, C*H*$_2$C(OH), 1H, *J* = 16.5 Hz, *J* = 1.5 Hz], 2.80 [d, C*H*$_2$C(OH), 1H, *J* = 16.5 Hz], 3.88 (broad, O*H*, 1H), 4.22–4.39 (m, COOC*H*$_2$, 2H), 4.94 (t, C=C*H*$_2$, 1H, *J* = 1.2 Hz), 4.97 (d, C=C*H*$_2$, 1H, *J* = 1.3 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 13.79, 28.91, 30.79, 36.49, 63.64, 77.97 (q, $J_{C,F}$ = 28.0 Hz), 108.84, 123.50 (q, $J_{C,F}$ = 287.5 Hz), 150.46, 169.78; ^{19}F{^{1}H} NMR ($CDCl_3$, 376 MHz): δ = −79.56; HR-MS (ESI): m/z = 291.1166, calcd. for $C_{12}H_{19}F_3O_3Na$ [M + Na]$^+$: 291.1179. The enantiomeric excess was determined by GC using a Varian CP7502 column (50 °C for 2 min; ramp to 110 °C at 10 °C min^{-1} and hold 20 min; then ramp to 180 °C at 10 °C min^{-1} and hold 5 min, gas flow: 1 mL min^{-1}): R_t of the major enantiomer = 13.0 min, R_t of the minor enantiomer = 13.7 min.

Ethyl 2-Hydroxy-6,6-dimethyl-4-methylene-2-(trifluoromethyl)-heptanoate (4d)

The title compound was prepared according to the general procedure using 0.25 mmol of ethyl trifluoropyruvate and 0.25 mmol of 2,4,4-trimethyl-1-pentene. The pure product was obtained by column chromatography over silica gel eluted with hexane/ethyl acetate (15:1). ^{1}H NMR ($CDCl_3$, 400 MHz): δ = 0.83 [s, C(C*H*$_3$)$_3$, 9H], 1.28 (t, OCH$_2$C*H*$_3$, 3H, *J* = 7.2 Hz), 1.81 [d, C*H*$_2$-C(CH$_3$)$_3$, 1H, *J* = 13.1 Hz], 2.03 [d, C*H*$_2$-C(CH$_3$)$_3$, 1H, *J* = 13.1 Hz], 2.57 [dd, C*H*$_2$-C(OH), 1H, *J* = 14.1 Hz, *J* = 0.7 Hz], 2.68 [d, C*H*$_2$-C(OH), 1H, *J* = 14.1 Hz], 3.77 (broad, -O*H*, 1H), 4.19–4.34 (m, COOC*H*$_2$, 2H), 4.81 (t, C=C*H*$_2$, 1H, *J* = 0.8 Hz), 4.95 (s, C=C*H*$_2$, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 13.91, 29.66, 31.68, 38.39, 50.39, 63.64, 78.35 (q, $J_{C,F}$ = 28.2 Hz), 118.29, 123.32 (q, $J_{C,F}$ = 286.5 Hz), 140.36, 169.51; ^{19}F{^{1}H} NMR ($CDCl_3$, 376 MHz): δ = −78.85; HR-MS (ESI): *m/z* = 305.1325, calcd. for $C_{13}H_{21}F_3O_3Na$ [M + Na]$^+$: 305.1335. The enantiomeric excess was determined by GC using a Varian CP7502 column (50 °C for 2 min; ramp to 110 °C at 10 °C min^{-1} and hold 20 min; then ramp to 180 °C at 10 °C min^{-1} and hold 5 min, gas flow: 1 mL min^{-1}): R_t of the major enantiomer = 15.5 min, R_t of the minor enantiomer = 16.5 min.

Ethyl 2-Hydroxy-4-phenyl-2-(trifluoromethyl)pent-4-enoate (4e)

The title compound was prepared according to the general procedure using 0.25 mmol of ethyl trifluoropyruvate and 0.25 mmol of α-methylstyrene. The pure product was obtained by column chromatography over silica gel eluted with hexane/ethyl acetate (15:1). ^{1}H NMR ($CDCl_3$, 400 MHz): δ = 1.03 (t, OCH$_2$C*H*$_3$, 3H, *J* = 7.2 Hz), 2.96 [dd, C*H*$_2$-C(OH), 1H, *J* = 14.0 Hz, *J* = 0.7 Hz], 3.21 [d, C*H*$_2$-C(OH), 1H, *J* = 14.0 Hz], 3.51–3.59 (m, COOC*H*$_2$, 1H), 3.72 (s, broad, O*H*, 1H), 3.91–3.99 (m, COOC*H*$_2$, 1H), 5.21 (d, C=C*H*$_2$, 1H, *J* = 0.9 Hz), 5.31 (d, C=C*H*$_2$, 1H, *J* = 1.3 Hz), 7.18–7.25 (m, Ph-*H*, 5H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 13.55, 37.03 (q, $J_{C,F}$ = 1.1 Hz), 63.49, 77.11 (q, $J_{C,F}$ = 28.7 Hz), 119.45, 123.38 (q, $J_{C,F}$ = 286.1 Hz), 126.78, 127.73, 128.16, 141.02, 141.04, 168.95; ^{19}F{^{1}H} NMR ($CDCl_3$, 376 MHz): δ = −78.62; HR-MS (ESI): m/z = 311.0857, calcd. for $C_{14}H_{15}F_3O_3Na$ [M + Na]$^+$: 311.0866. The enantiomeric excess was determined by HPLC with a Chiralpak AS-H column (0.5% 2-propanol in hexane, flow 0.3 mL min^{-1}): R_t of the major enantiomer = 16.0 min, R_t of the minor enantiomer = 17.2 min).

Ethyl 2-Hydroxy-4-phenyl-4-pentenoate (5e)

The title compound was prepared according to the general procedure using 0.5 mmol ethyl glyoxylate (50% in toluene) and 0.25 mmol α-methylstyrene. The pure product was obtained by column chromatography over silica gel eluted with heyane/ethyl acetate (5:1). The ^{1}H NMR and ^{13}C NMR spectra of the product were consistent with reported data.[5a,b] The enantiomeric excess was determined by HPLC with a chiral AS column (5.0% 2-propanol in hexane, flow 1.0 mL min^{-1}): (*S*)-enantiomer $R_t = 11$ min (minor), (*R*)-enantiomer $R_t = 17$ min (major).

Supporting Information

^{1}H NMR, ^{13}C NMR, ^{19}F{H} NMR, HPLC and GC traces of products **3c'**and **4a–4e** are given in the Supporting Information.

Acknowledgements

*This work was supported by Institute of Chemical and Engineering Sciences, A*STAR, Singapore.*

References

[1] a) J. A. Switzer, H. M. Kothari, P. Poizot, S. Nakanishi, E. W. Bohannan, *Nature* **2003**, *425*, 490–493; b) M. O. Lorenzo, C. J. Baddeley, C. Muryn, R. Raval, *Nature* **2000**, *404*, 376–379; c) A. Vargas, D. Ferri, N. Bonalumi, T. Mallat, A. Baiker, *Angew. Chem.* **2007**, *119*, 3979–3982; *Angew. Chem. Int. Ed.* **2007**, *46*, 3905–3908; d) N. Bonalumi, A. Vargas, D. Ferri, T. Burgi, T. Mallat, A. Baiker, *J. Am. Chem. Soc.* **2005**, *127*, 8467–8477; e) B. Qin, X. Xiao, X. Liu, J. Huang, Y. Wen, X. Feng, *J. Org. Chem.* **2007**, *72*, 9323–9328; f) D. Z. Wang, *Tetrahedron* **2005**, *61*, 7134–7143.

[2] For catalyst based on Al, see: K. Maruoka, Y. Hoshino, T. Shirasaka, H. Yamamoto, *Tetrahedron Lett.* **1988**, *29*, 3967–3970.

[3] For catalysts based on Ti, see: a) K. Mikami, M. Terada, T. Nakai, *J. Am. Chem. Soc.* **1989**, *111*, 1940–1941; b) K. Mikami, M. Terada, T. Nakai, *J. Am. Chem. Soc.* **1990**, *112*, 3949–3954; c) K. Mikami, *Pure & Appl. Chem.* **1996**, *68*, 639–644; d) Y. M. A. Yamada, M. Ichinohe, H. Takahashi, S. Ikegami, *Tetrahedron Lett.* **2002**, *43*, 3431–3434; e) Y. Yuan, X. Zhang, K. Ding, *Angew. Chem.* **2003**, *115*, 5636–5638; *Angew. Chem. Int. Ed.* **2003**, *42*, 5478–5480; f) H. Guo, X. Wang, K. Ding, *Tetrahedron Lett.* **2004**, *45*, 2009–2012.

[4] For catalysts based on Cr, see: a) R. T. Ruck, E. N. Jacobsen, *J. Am. Chem. Soc.* **2002**, *124*, 2882–2883; b) R. T. Ruck, E. N. Jacobsen, *Angew. Chem.* **2003**, *115*, 4919–4922; *Angew. Chem. Int. Ed.* **2003**, *42*, 4771–4774; c) W. Chaładaj, P. Kwiatkowski, J. Majer, J. Jurczak, *Tetrahedron Lett.* **2007**, *48*, 2405–2408.

[5] For catalysts based on Cu, see: a) D. A. Evans, C. S. Burgey, N. A. Paras, T. Vojkovsky, S. W. Tregay, *J. Am. Chem. Soc.* **1998**, *120*, 5824–5825; b) D. A. Evans, S. W. Tregay, C. S. Burgey, N. A. Paras, T. Vojkovsky, *J. Am. Chem. Soc.* **2000**, *122*, 7936–7943; c) C. McDonagh, P. O'Leary, *Tetrahedron Lett.* **2009**, *50*, 979–982.

[6] For catalysts based on Co, see: a) S. Kezuka, T. Ikeno, T. Yamada, *Org. Lett.* **2001**, *3*, 1937–1939; b) G. E. Hutson, A. H. Dave, V. H. Rawal, *Org. Lett.* **2007**, *9*, 3869–3872.

[7] For catalysts based on Pd and Pt with chiral diphosphines, see: a) J. Hao, M. Hatano, K. Mikami, *Org. Lett.* **2000**, *2*, 4059–4062; b) J. H. Koh, A. O. Larsen, M. R. Gagné, *Org. Lett.* **2001**, *3*, 1233–1236; c) K. Aikawa, S. Kainuma, M. Hatano, K. Mikami, *Tetrahedron Lett.* **2004**, *45*, 183–185; d) K. Mikami, K. Aikawa, S. Kainuma, Y. Kawakami, T. Saito, N. Sayo, H. Kumobayashi, *Tetrahedron: Asymmetry* **2004**, *15*, 3885–3889; e) K. Mikami, H. Kakuno, K. Aikawa, *Angew. Chem.* **2005**, *117*, 7423–7426; *Angew. Chem. Int. Ed.* **2005**, *44*, 7257–7260; f) H.-K. Luo, B.-K. Lim, H. Schumann, C. Lim, X.-J. Tan, H.-Y. Yang, *Adv. Synth. Catal.* **2007**, *349*, 1781–1795.

[8] For catalysts based on Sc, see: D. A. Evans, J. Wu, *J. Am. Chem. Soc.* **2005**, *127*, 8006–8007.

[9] For catalysts based on In, see: a) J. Lu, M.-L. Hong, S.-J. Ji, T.-P. Loh, *Chem. Commun.* **2005**, 1010–1012; b) J.-F. Zhao, H.-Y. Tsui, P.-J. Wu, J. Lu, T.-P. Loh, *J. Am. Chem. Soc.* **2008**, *130*, 16492–16493.

[10] For catalysts based on Ni, see: K. Zheng, J. Shi, X. Liu, X. Feng, *J. Am. Chem. Soc.* **2008**, *130*, 15770–15771.

[11] a) B. K. Corkey, F. D. Toste, *J. Am. Chem. Soc.* **2007**, *129*, 2764–2765; b) D. Xiao, Z. Zhang, X. Zhang, *Org. Lett.* **1999**, *1*, 1679–1681; c) W. Tang, W. Wang, Y. Chi, X. Zhang, *Angew. Chem.* **2003**, *115*, 3633–3635; *Angew. Chem. Int. Ed.* **2003**, *42*, 3509–3511; d) A. T. Axtell, J. Klosin, K. A. Abboud, *Organometallics* **2006**, *25*, 5003–5009; e) M. J. Burk, J. E. Feaster, W. A. Nugent, R. L. Harlow, *J. Am. Chem. Soc.* **1993**, *115*, 10125–10138.

[12] T. J. Brunker, N. F. Blank, J. R. Moncarz, C. Scriban, B. J. Anderson, D. S. Glueck, L. N. Zakharov, J. A. Golen, R. D. Sommer, C. D. Incarvito, A. L. Rheingold, *Organometallics* **2005**, *24*, 2730–2746.

