DOI: 10.1002/adsc.200600623

Electronic and Steric Effects of Atropisomeric Ligands SYNPHOS® and DIFLUORPHOS® *vs.* BINAPs in Rh(I)-Catalyzed Asymmetric Pauson–Khand Reaction

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Received: December 4, 2006; Revised: June 4, 2007

Supporting information for this article is available on the WWW under http://asc.wiley-vch.de/home/.

Abstract: The electronic and steric effects of chiral biaryl diphosphine ligands on the Rh(I)-catalyzed asymmetric Pauson–Khand type reaction were examined. We demonstrated that enantioselectivity and reaction yield were influenced by the electronic density on phosphorus, the dihedral angle of ligands and the electronic density of the alkyne substrate. Ligands bearing a narrower dihedral angle than Binap, such as Synphos (**L4**) and Difluorphos (**L5**), were found to increase substantially the enantioselectivity of the reaction, compared to Binap-type ligands. Ligands having a deshielded phosphine, such as *p*-CF_3-Binap (**L3**) and Difluorphos (**L5**) provided better enantioselectivity than Binap, with reduced formation of side products, especially with electron-poor alkyne substrates.

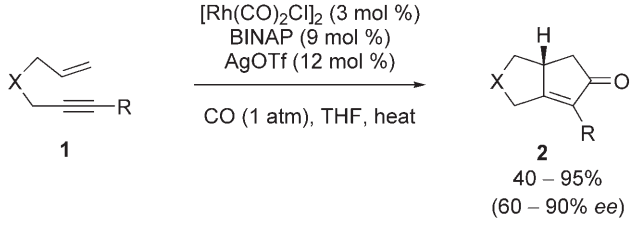
Keywords: atropisomeric ligands; electronic effects; enantioselectivity; Pauson–Khand reaction; steric effects

Introduction

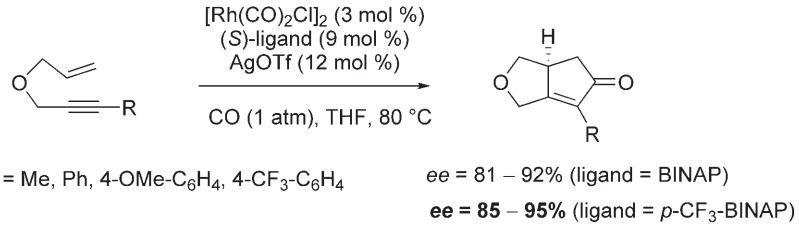
In recent years, a great deal of research has been devoted to the asymmetric catalytic Pauson–Khand reaction (denoted as the PKR hereafter),[1] which is defined as the transition metal mediated [2+2+1] cycloaddition of an alkyne, an alkene and CO.[2] Various versions of the enantioselective PK type reaction using cobalt,[3] titanium,[4] rhodium[5] and iridium[6] together with chiral ligands have been published.[3] Several years ago, we described the first rhodium-catalyzed enantioselective PKR under a CO atmosphere in the presence of an atropisomeric ligand (Scheme 1).[5] These early results were promising in terms of enantioselectivity, but they also exhibited some limitations with certain classes of substrates.

Efforts to optimize this methodology were reported,[7] but improvements in terms of enantioselectivity and chemical yield still need to be realized. In a previous paper,[8] we performed a systematic screening of twelve different classical PKR 1,6-enyne substrates and six Binap-type ligands displaying different electronic properties. Accurate interpretation of the results showed a clear tendancy: for a given Binap ligand, the more electron-rich the alkyne, the better the enantioselectivity (but the lower the yield); for a given sustrate, the more electron-poor the Binap ligand, the higher the enantioselectivity (almost no influence on the yield). Especially enantioselectivities obtained with *p*-CF_3-Binap ligand, bearing a far lower electronic density on phosphorus than Binap, were 2 to 5% higher than those obtained with Binap, as shown on Scheme 2.

In the present study, we wished to get a deeper insight in designing an optimized Rh(I)/ligand catalyst for enantioselective PKR under CO atmosphere, by



Scheme 1. The Rh(I)-catalyzed asymmetric PKR.



Scheme 2.

evaluating the performance of Synphos[9] and Difluorphos[10] ligands in this reaction, in comparison to Binap family ligands.

Results and Discussion

The biaryldiphosphine ligands used in this study were chosen to permit distinct examination of their steric and electronic influence on the stereochemical outcome of the reaction. Binap ligand (**L2**) was chosen as reference. *p*-OMe-Binap (**L1**) and *p*-CF_3-Binap (**L3**) ligands were selected because they have geometric properties similar to Binap, but different electronic features. Synphos (**L4**) and Difluorphos (**L5**) ligands proved to give better selectivities than Binap in several enantioselective transition metal-catalyzed reactions of C–H[10] or C–C[11] bond formation, using Ru, Rh or Ag catalysts. As far as the Ru(II)-mediated asymmetric hydrogenation of prochiral α- or β-keto esters is concerned, we showed in a previous study[10b] that a smaller dihedral angle (θ in Figure 1) of the biaryl backbone in the geometrical structure of **L4** and **L5** was responsible for their better performance in this particular reaction, compared to Binap. Thus we wished to evaluate the influence of steric and electronic properties of these five ligands **L1–L5** on the yield and enantioselctivity in Rh-mediated PKR.

The quantification of steric properties of atropisomeric diphosphines is conveniently achieved by measuring the dihedral angle θ of the biaryl backbone using molecular modeling techniques, as shown in Table 1. Although the biaryl moiety is a flexible backbone, allowing atropisomeric ligands to adapt their geometrical structure to the coordination sphere of the metal, the relative order of θ for **L1–L5** is independent of the type of molecular structure containing the diphosphine (free ligand, Pd or Rh complexes): $\theta(\mathbf{L1}) \sim \theta(\mathbf{L2}) \sim \theta(\mathbf{L3}) > \theta(\mathbf{L4}) > \theta(\mathbf{L5})$. The tetraoxygenated biaryl core of Synphos (**L4**) and Difluorphos (**L5**) confers to these ligands a narrower dihedral angle than the binaphthyl-based diphosphines **L1**, **L2** and **L3**.

Regarding the comparative electronic profiles of the diphosphines **L1–L5**, this can be evaluated by several described methods.[13] First we quantified the electronic density on phosphorus through ^{31}P NMR spectra of free ligands (Table 2): the higher the ^{31}P chemical shift, the more electron-poor the ligand. Synphos (**L4**) and Binap (**L2**) free ligands seem to

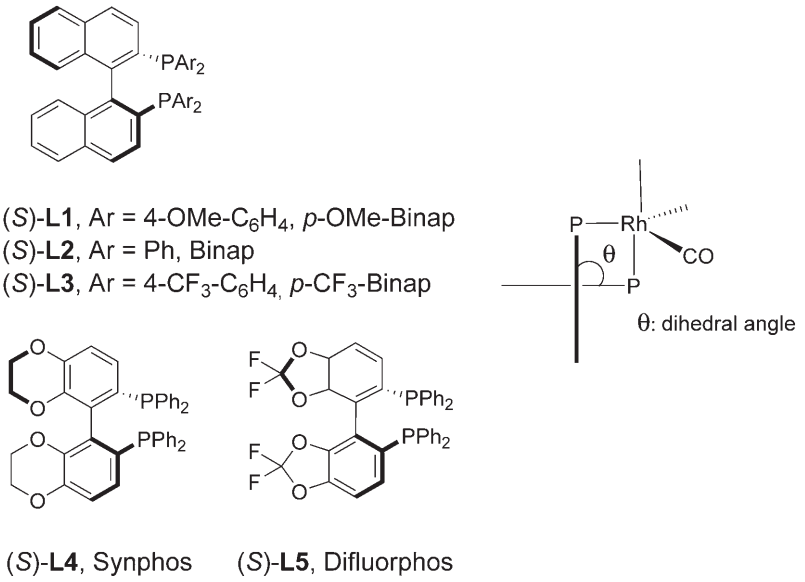


Figure 1. The ligands used in this study.

Table 1. Steric properties of biaryl diphosphine ligands **L1–L5** (key steric parameter = dihedral angle of biaryl backbone θ).

Ligand (L*)		Dihedral angle of free ligand[a] (θ, °)	Dihedral angle of ligand (L*) in [$PdCl_2$ (L*)][a] (θ, °)	Dihedral angle of ligand (L*) in [RhCl(CO)(L*)][a] (θ, °)
L1	*p*-OMe-Binap	85.2	79.2	78.3
L2	Binap	86.2	79.2	78.3
L3	*p*-CF_3-Binap	83.8	79.0	78.0
L4	Synphos	70.7	73.6	73.0
L5	Difluorphos	67.6	73.0	72.2

[a] Structures minimized by Molecular Mechanics calculations (CAChe MM2 program).[12]

Table 2. Electronic properties of biaryl diphosphine ligands **L1–L5**.

Ligand (L*)		^{31}P NMR chemical shift ($CDCl_3$) (δ, ppm)	IR carbonyl stretching frequency in [RhCl(CO)(L*)] from THF [ν(CO), cm^{-1}][a]
L1	*p*-OMe-Binap	−16.9	1998
L2	Binap	−14.4	2003
L3	*p*-CF_3-Binap	−13.8	2022
L4	Synphos	−14.3	2000
L5	Difluorphos	−12.5	2014

[a] This parameter quantifies the electronic donor-acceptor properties of the diphophine ligand (L*) when chelated to a transition metal: the higher the carbonyl stretching frequency, the higher the π-acidic character of the diphosphine.[13b]

have similar electronic properties (−14.3 and −14.4 ppm, respectively), *p*-CF_3-Binap (**L3**) and Difluorphos (**L5**) reveal a less basic profile than Binap (−13.8 and −12.5 ppm, respectively), Difluorphos (**L5**) being the most electron-poor ligand of the series. As expected, *p*-OMe-Binap **L1** is the most electron-rich ligand of the series, displaying a chemical shift of −16.9 ppm. In order to complete this electronic evaluation with data relative to chelated diphosphines, we synthesized the [Rh(CO)Cl(ligand)] complexes according to the reported procedure[13b] and evaluated the IR stretching frequency of the carbonyl ligand in these complexes for **L1** through **L5**: the higher the frequency, the higher the π-acidic character of the chelated diphosphine. As reported in Table 2, the five diphosphines ordered by decreasing π-acidity are as follows: *p*-CF_3-Binap [**L3**, $\nu(CO) = 2022\ cm^{-1}$] > Difluorphos [**L5**, $\nu(CO) = 2014\ cm^{-1}$] > Binap [**L2**, $\nu(CO) = 2003\ cm^{-1}$] > Synphos [**L4**, $\nu(CO) = 2000\ cm^{-1}$] > *p*-OMe-Binap [**L1**, $\nu(CO) = 1998\ cm^{-1}$]. These results confirm that Lewis acidity of the catalyst is not merely a reflection of electronic effects, instead it is influenced by geometrical factors as well. Thus, Synphos **L4** makes the catalyst more Lewis basic than Binap when chelated to a transition metal, whereas *p*-CF_3-Binap **L3** and Difluorphos **L5** are far more electron-poor.

Figure 2 summarizes the comparative steric and electronic profiling of ligands **L1–L5**: two ligands (*p*-

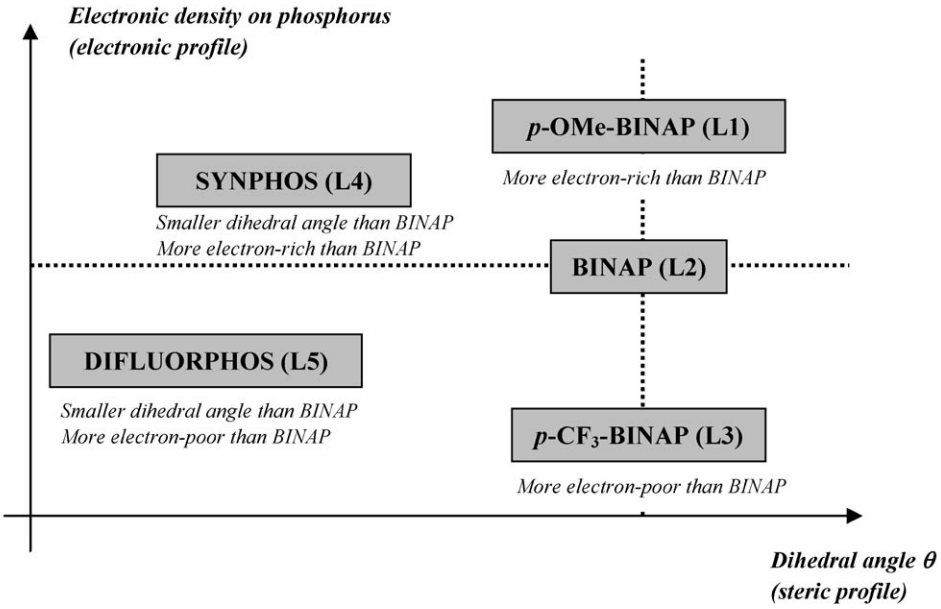


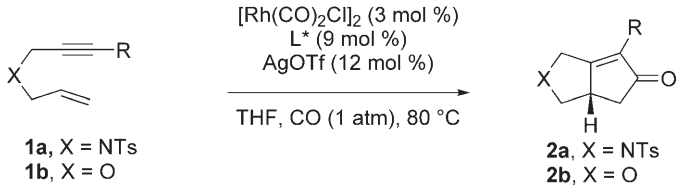
Figure 2. Comparative stereoelectronic profiles of ligands **L1–L5.**

OMe-Binap **L1** and Synphos **L4**) are more electron-rich than Binap (**L2**); whereas geometric properties of **L1** are identical to those of Binap, Synphos **L4** bears a narrower dihedral angle than Binap, making the steric hindrance of diphenylphosphino groups around the metal more important. The two remaining diphosphines **L3** (*p*-CF_3-Binap) and **L5** (Difluorphos) are both more electron-poor than Binap but display different steric features: dihedral angle of Difluorphos (**L5**) is narrower than those of Binap (**L2**) and *p*-CF_3-Binap (**L3**).

Having in hand a quantitative steric and electronic evaluation of the diphosphine ligands **L1** to **L5**, we investigated their performances as chiral inductors in asymmetric Rh-mediated PKR under CO atmosphere. Representative substrates for the study were selected in order to reflect the effects of electronic character on the alkynes. These can be divided into the alkyl-substituted alkynes (**1a-1** and **1b-1**) and the aryl-substituted alkynes, which were further differentiated electronically by the substituents on the *para* position of the phenyl ring (**1a-2**, **1a-3**, **1a-4** for *N*-tosyl tethered substrates and **1b-2**, **1b-3** and **1b-4** for *O*-tethered substrates). A typical reaction was carried out with catalyst prepared by mixing tetracarbonyldi-μ-chlorodirhodium {$[Rh(CO)_2Cl]_2$} and the selected disphosphine ligand in tetrahydrofuran for 30 min at ambient temperature under an argon atmosphere. The substrate was introduced into the mixture, the argon atmosphere was replaced by carbon monoxide (1 atm) and the mixture was heated to 80 °C until complete conversion of starting material. The results are summarized in Table 3.

As we noticed in our previous study,[8] for a given ligand, the more electron-poor the substrate, the poorer the enantioselectivity (but the better the yield). This clear tendency can be checked in any entry of Table 3, as illustrated, for example, in entry 2 for Binap ligand: ee(**2a-1**) = 83 % > ee(**2a-2**) = 71 % > ee(**2a-3**) = 65 % > ee(**2a-4**) = 63 %. As a result, only electron-rich cyclopentenone compounds **2a-1** and **2b-1** could be obtained with ee > 92 %. For these two

Table 3. Rh(I)-catalyzed enantioselective PKR with various ligands **L1–L5** (preferred ligand/substrate pairs shown in shaded boxes).



1a, X = NTs
1b, X = O

2a, X = NTs
2b, X = O

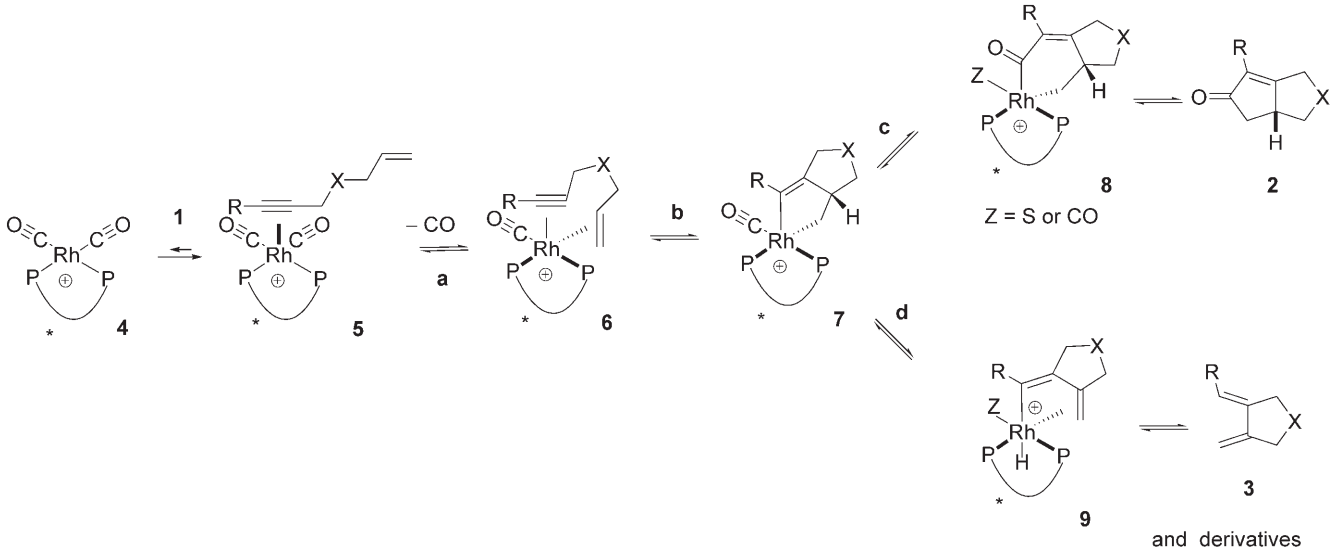
Entry	Ligand		X	R = Me (**1**)			R = 4-$MeOC_6H_4$ (**2**)			R = C_6H_5 (**3**)			R = 4-$CF_3C_6H_4$ (**4**)		
				t[c] [h]	Yield [%]	ee [%][a]	t[c] [h]	Yield [%]	ee [%][b]	t[c] [h]	Yield [%]	ee [%][a]	t[c] [h]	Yield [%]	ee [%][b]
1	(*S*)-**L1**	*p*-OMe-Binap		0.5	53	81	0.5	70	70	0.5	99	60	1.5	95	60
2	(*S*)-**L2**	Binap	*N*Ts	0.5	70	83	4	92	71	3	99	65	4	99	63
3	(*S*)-**L3**	*p*-CF_3-Binap		0.5	65	84	3	97	75	2.5	97	67	4	98	68
4	(*S*)-**L4**	Synphos	(**1a**)	0.5	57	93	1.5	74	89	2.5	98	65	4	93	68
5	(*S*)-**L5**	Difluorphos		0.5	62	89	0.5	90	75	2	90	70	3.5	90	71
6	(*S*)-**L1**	*p*-OMe-Binap		0.5	33	85	0.5	65	73	0.5	67	64	1	81	69
7	(*S*)-**L2**	Binap	O	0.5	42	92	2	75	85	1.5	72	85	1	82	81
8	(*S*)-**L3**	*p*-CF_3-Binap		0.5	44	95	4	84	87	3	89	90	1	85	85
9	(*S*)-**L4**	Synphos	(**1b**)	0.5	42	98	1.5	56	89	1	75	85	1.5	82	85
10	(*S*)-**L5**	Difluorphos		0.5	38	94	0.5	70	91	1	81	87	0.5	80	90

[a] (*S*)-**2a** is a major product when the absolute configuration of ligand employed is (*S*).[5a]
[b] The absolute configuration of these products has not been determined.
[c] Time for the complete consumption of starting materials.

PKR products, but also for compound **2a-2**, the preferred ligand/substrate pairs were obtained with Synphos (**L4**) as illustrated by shaded boxes in Table 3 (*ee* = 89–98 % compared to 71–92 % with Binap), which represent a significant increase in enantioselectivity of +6 % (for substrate **1b-1**) to +18 % (for substrate **1a-2**), compared to Binap. However these enhancements in selectivity are tainted by a significant loss of chemical yield with Synphos ligand, as illustrated, for example, with substrate **1a-1** and **1a-2** (entry 4), which were converted into **2a-1** and **2a-2** in only 57 % and 74 % yields, respectively (to be compared with 70 % and 92 % yields obtained with Binap – entry 2). This decrease in chemical yield with electron-rich alkynes **1a-1** and **1a-2** is also observed with *p*-OMe-Binap **L1** (53 % and 70 % yield, respectively, for the same substrates – entry 1); therefore one could argue that the use of electron-rich ligands is detrimental to the yield for these substrates, which means that the competitive formation of side products became more significant.[14]

This result prompts a brief look at the reaction mechanism proposed in Scheme 3. Step b, which consists of the oxidative formation of metallacyclopentene **7** is considered to be the rate- and stereo-determining step of the reaction.[8] Therefore, two diastereoisomeric transition states can lead to complex **7**. In asymmetric catalysis, it is usually admitted that improvement of enantioselectivity would be the result of an increased difference in energy between these two competing diastereomeric transition states. Nevertheless, if Rh/Synphos complex is associated with electron-rich PKR substrates, there is a significant relationship between enantioselectivity and yield (increase in selectivity at the expense of yield), so one cannot rule out completely the possibility of a kinetic differentiation during the reaction. In other words, one diastereomeric intermediate of **7** is mostly prone to follow the pathway giving Pauson–Khand reaction products **2** (through intermediate **8**, Scheme 3), whereas the other diastereomeric intermediate of **7** is prone to give products derived from **3** by taking the other reaction pathway through intermediate **9**. Thus, the reaction provides the higher enantioselectivity only with the sacrifice of chemical yield of the desired PKR product **2**. In summary, it seems that kinetic differenciation occurs preferably with electron-rich alkyne substates **1a-1**, **1a-2**, **1b-1** and **1b-2** and with Synphos ligand (**L4**) exclusively. Indeed, using electron-richer *p*-OMe-Binap (**L1**) instead of Binap (**L2**) with these substrates makes the yield decrease significantly but has almost no positive influence on the enantioselectivity, which reveals a rather different behavior than Synphos.

As mentioned earlier, electron-deficient *N*-tosylated alkynes **1a-3** and **1a-4** are considered as challenging PKR substrates, in that Rh complexes bearing ligands **L1**, **L2** or **L3** (Binap-type) failed to catalyze the reaction with high enantioselectivity (*ee* = 60–68 %, entries 1, 2 and 3). For these substrates, dihedral angle of the ligand is not a critical parameter to design the best enantioselective catalyst, in that Synphos (**L4**) gives results comparable to Binap (*ee* = 65 % for substrate **1a-3**) and *ee*s are more sensitive to the electronic properties of the ligand: the more electron-poor the ligand, the better the enantioselection. Therefore, electron-poor diphosphines give the best selectivities for product **2a-3** [*ee* = 67 % with *p*-CF_3-Binap (**L3**), *ee* = 70 % with Difluorphos (**L5**)]. Extrapolating this observation, one could expect that biaryldiphosphines bearing more electron-deficient substituents than Difluorphos would improve this mild result further.



Scheme 3. A proposed mechanism for the Rh(I)-catalyzed asymmetric Pauson–Khand-type reaction under CO atmosphere.

As underlined by grey boxes in Table 3, Difluorphos (**L5**) and *p*-CF_3-Binap (**L3**) ligands display the best performances with this catalytic system in terms of chemical yield and enantioselectivity (see entries 5, 8 and 10), especially preferred ligand/substrate pairs were obtained with compounds **1a-3**, **1a-4** (*ee* = 70–71%) and more remarkably with *O*-tethered 1,6-enynes **1b-2**–**1b-4**, for which very good *ee*s of 90–91% could be reached (only 81–85% *ee* with Binap). For these substrates, the electronic profile of Difluorphos (**L5**) and *p*-CF_3-Binap (**L3**) (with a lower electronic density on phosphorus than Binap) is responsible for the improved enantioselectivity from Synphos **L4** and Binap ligands (**L1** and **L2**). Noticeably, and contrary to what we observed with Synphos and electron-rich alkynes, this increase in enantioselectivity with these ligands is not accompanied with a loss of chemical yield. Good to excellent yields were obtained ranging from 70% for **2b-2** (*ee* = 91%) and 90% for **2a-4** (*ee* = 71%) with Difluorphos **L5**. Even better chemical yields (+7% for **2a-2** and **2b-2** to +14% for **2b-3**) with somewhat inferior enantioselectivities (−3 to −5%) were obtained by *p*-CF_3-Binap (**L3**) with exception of **2b-3**. For example, 84% yield for **2b-2** with 87% *ee* and 98% yield for **2a-4** with 68% *ee* were obtained with **L3**.

It is also evident that the ligands having narrower dihedral angle accelerated the reaction significantly more than Binap-based ligands. Synphos **L4**, which has narrower dihedral angle than Binap **L2** but with a similar chemical shift of phosphorus, completed the reaction in a shorter period. In addition, Difluorphos (**L5**), whose phosphorus is more deshielded than that of *p*-CF_3-Binap (**L3**), leads the reaction to completion in a shorter time. However, this acceleration is often associated with a loss of chemical yield in certain cases (for **2a-2**, **2a-3**, **2b-2** and **2b-3**).

Conclusions

We have demonstrated that the enantioselectivity and yield of the catalytic Pauson–Khand reaction depends on both the electronic density and dihedral angle of the diphosphine ligand, as well as on the electronic density of the alkyne moiety of the 1,6-enyne PKR substrate. As we considered it to be utopical to design a universal Rh catalytic system for the Pauson–Khand reaction under a CO atmosphere, we targeted and identified preferred ligand/substrate correspondences providing the best yields and enantioselectivities, and identified general trends to optimize the methodology. As an important complement to our previous study in this area,[8] we found that steric properties of the biaryl backbone of the ligand, especially the value of its dihedral angle θ, play a crucial role in the stereochemical outcome of Rh-mediated PKR: Synphos **L4** and Difluorphos **L5**, with a narrower dihedral angle than Binap-type ligands, give improved reactivities and enantioselectivities for most substrates (*ee*s up to 98% for Synphos ligand and up to 91% for Difluorphos ligand). However, this increase in selectivity is often reached at the expense of chemical yield, certainly explained by a preferential kinetic differentiation pathway. Electronic adequation between substrate and ligand was confirmed as a crucial point to reach high enantioselectivities: electron-rich alkyne substrates **1a-1**, **1a-2** and **1b-1** were converted in moderate yield (42–74%) but excellent enantioselectivities (89–98%) to their corresponding PKR product using electron-rich Rh/Synphos complexes; on the contrary electron-deficient enynes **1a-3**, **1a-4**, **1b-3** and **1b-4** provided the best yields (80–90%) and enantioselectivities (70–91%) when Difluorphos (**L5**) or *p*-CF_3-Binap (**L3**) were used as chiral inductors, essentially because of their low electronic density on phosphorus.

Experimental Section

Representative Procedure for Catalytic Enantioselective Pauson–Khand Reaction

6-Methyl-2-(4-toluenesulfonyl)-2,3,3a,4-tetrahydro-1*H*-cyclopenta[*c*]pyrrol-5-one (**2a-1**):[5] $[Rh(CO)_2Cl]_2$ (1.3 mg, 0.003 mmol, 3 mol%) and (*S*)-Synphos (6.6 mg, 0.010 mmol, 9 mol%) were placed in THF (1 mL) and the mixture was stirred for 30 min at 20 °C under atmospheric pressure of argon. A solution of AgOTf (3.5 mg, 0.014 mmol, 12 mol%) in THF (1 mL) was added, and the resultant reaction mixture was stirred for another 30 min at 20 °C. The argon atmosphere was replaced with CO (1 atm), and then a solution of **1a-1** (30 mg, 0.114 mmol) in THF (1 mL) was introduced. The reaction mixture was heated at 80 °C. After completion of the reaction, the reaction mixture was cooled to room temperature and the carbon monoxide was released in the hood. The crude reaction mixtures were directly purified by column chromatography on silica gel using *n*-hexane/ethyl acetate mixture as the eluent to afford PKR product **2a-1** (19 mg, 0.065 mmol, 57%). The enantiomeric excess of the product **2a-1** was determined by HPLC analysis using Daicel columns (CHIRALPAK AD-H, 0.46 mm I.D. × 25 cm, *n*-hexane/2-PrOH = 4/1, flow 0.8 mL min^{-1}, 254 nm): t_R = 13.08 min (minor) and 13.94 min (major). The *ee* was determined to be 93% when (*S*)-Synphos was used.

Determination of Enantiomeric Purity

The enantiomeric excesses of the other products were determined by chiral HPLC analysis using Daicel columns (0.46 mm I.D. × 25 cm) as specified.

6-(4-Methoxyphenyl)-2-(4-toluenesulfonyl)-2,3,3a,4-tetrahydro-1*H*-cyclopenta[*c*]pyrrol-5-one (**2a-2**): The *ee* value was determined by HPLC analysis using a chiral column (DAICEL CHIRALPAK AD, *n*-hexane/2-PrOH = 3/1, 1.2 mL min^{-1}, 254 nm): t_R = 17.16 min (minor) and 19.06 min

(major). The *ee* was determined to be 89% when (*S*)-Synphos was used. $[\alpha]_D^{21}$: −4.50 (*c* 1.3, CH_2Cl_2); IR (KBr): ν = 1705 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): δ = 2.22 (dd, *J* = 18.0 and 3.0 Hz, 1H), 2.40 (s, 3H), 2.58 (dd, *J* = 18.0 and 15.0 Hz, 1H), 2.76 (dd, *J* = 18.0 and 6.0 Hz, 1H), 3.07–3.22 (m, 1H), 3.82 (s, 3H), 4.04 (dd, *J* = 18.0 and 6.0 Hz, 1H), 4.07 (d, *J* = 18.0 Hz, 1H), 4.60 (d, *J* = 18.0 Hz, 1H), 6.92 (d, *J* = 8.5 Hz, 2H), 7.30 (d, *J* = 8.0 Hz, 2H), 7.42 (d, *J* = 8.5 Hz, 2H), 7.71 (d, *J* = 8.0 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 21.8, 40.9, 41.9, 48.7, 52.3, 55.6, 114.3, 122.7, 127.6, 129.8, 130.2, 133.9, 135.7, 144.3, 160.3, 170.0, 206.1; HR-MS (FAB$^+$): *m/z* $[M+Na]^+$ calcd. for $C_{21}H_{21}NO_4SNa$: 406.1089; found: 406.1078.

6-Phenyl-2-(4-toluenesulfonyl)-2,3,3a,4-tetrahydro-1*H*-cyclopenta[*c*]pyrrol-5-one (**2a-3**):[5a] The *ee* value was determined by HPLC analysis using a chiral column (DAICEL CHIRALPAK AD-H, *n*-hexane/2-PrOH = 3/1, 1.2 mL min^{-1}, 254 nm): t_R = 11.15 min (minor) and 13.00 min (major). The *ee* was determined to be 70% when (*S*)-Difluorphos was used.

2-(4-Toluenesulfonyl)-6-(4-trifluoromethyl-phenyl)-2,3,3a,4-tetrahydro-1*H*-cyclopenta[*c*]pyrrol-5-one (**2a-4**): The *ee* value was determined by HPLC analysis using a chiral column (DAICEL CHIRALPAK AD-H, *n*-hexane/2-PrOH = 3/1, 1.2 mL min^{-1}, 254 nm): t_R = 24.07 min (major) and 25.77 min (minor). The *ee* was determined to be 71% when (*S*)-Difluorphos was used. $[\alpha]_D^{21}$: +42 (*c* 0.5, CH_2Cl_2). IR (KBr): ν = 1710 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): δ = 2.29 (dd, *J* = 18.0 and 3.7 Hz, 1H), 2.41 (s, 3H), 2.64 (dd, *J* = 12.0 and 9.6 Hz, 1H), 2.83 (dd, *J* = 18.0 and 6.6 Hz, 1H), 3.20–3.33 (m, 1H), 4.08 (dd, *J* = 18.0 and 6.0 Hz, 1H), 4.10 (d, *J* = 15.0 Hz, 1H), 4.66 (d, *J* = 15.0 Hz, 1H), 7.32 (d, *J* = 8.0 Hz, 2H), 7.62 (d, *J* = 8.2 Hz, 2H), 7.66 (d, *J* = 8.2 Hz, 2H), 7.72 (d, *J* = 8.0 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 21.8, 40.9, 42.4, 48.5, 52.1, 124.2 (q, *J* = 272 Hz), 125.8 (q, *J* = 8.3 Hz), 128.5, 130.6 (q, *J* = 30 Hz), 133.8, 134.2, 179.9, 206.5; HRMS (FAB+): *m/z* $[M+Na]^+$ calcd. for $C_{21}H_{18}F_3NO_3SNa$: 444.0857; found: 444.0863.

6-Methyl-3a,4-dihydro-1*H*,3*H*-cyclopenta[*c*]furan-5-one (**2b-1**):[5a] The *ee* value was determined by HPLC analysis using a chiral column (DAICEL CHIRALPAK AS-H, *n*-hexane/2-PrOH = 9/1, 1.0 mL min^{-1}, 254 nm): t_R = 12.69 min (major) and 12.48 min (minor). The *ee* was determined to be 98% when (*S*)-Synphos was used.

6-(4-Methoxyphenyl)-3a,4-dihydro-1*H*,3*H*-cyclopenta[*c*]-furan-5-one (**2b-2**): The *ee* value was determined by HPLC analysis using a chiral column (DAICEL CHIRALPAK AD-H, *n*-hexane/2-PrOH = 4/1, 1.0 mL min^{-1}, 254 nm): t_R = 11.53 min (minor) and 12.50 min (major). The *ee* was determined to be 91% when (*S*)-Difluorphos was used. $[\alpha]_D^{21}$: +1.97 (*c* 1.1, CH_2Cl_2). IR (KBr): ν = 1701 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): δ = 2.32 (dd, *J* = 17.7 and 3.2 Hz, 1H), 2.82 (dd, *J* = 17.7 and 6.0 Hz, 1H), 3.21 (dd, *J* = 12.0 and 6.0 Hz, 1H), 3.25–3.35 (m, 1H), 3.82 (s, 3H), 4.36 (dd, *J* = 12.0 and 9.0 Hz, 1H), 4.57 (d, *J* = 16.8 Hz, 1H), 4.91 (d, *J* = 16.8 Hz, 1H), 6.93 (d, *J* = 8.8 Hz, 2H), 7.48 (d, *J* = 8.8 Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 40.5, 43.4, 55.5, 66.6, 71.6, 114.3, 123.5, 129.6, 134.4, 160.0, 175.5, 207.5; HR-MS (EI+): *m/z* calcd. for $C_{14}H_{14}O_3$: 230.0943; found: 230.0944.

6-Phenyl-3a,4-dihydro-1*H*,3*H*-cyclopenta[*c*]furan-5-one (**2b-3**):[5a] The *ee* value was determined by HPLC analysis using a chiral column (DAICEL CHIRALPAK AD-H, *n*-hexane/2-PrOH = 4/1, 0.8 mL min^{-1}, 254 nm): t_R = 9.99 min (minor) and 12.13 min (major). The *ee* was determined to be 90% when (*S*)-*p*-CF_3-Binap was used.

6-(4-Trifluoromethylphenyl)-3a,4-dihydro-1*H*,3*H*-cyclopenta[*c*]furan-5-one (**2b-4**): The *ee* value was determined by HPLC analysis using a chiral column (DAICEL CHIRALPAK AS-H, *n*-hexane/2-PrOH = 9/1, 1.0 mL min^{-1}, 254 nm): t_R = 11.83 min (major) and 13.83 min (minor). The *ee* was determined to be 90% when (*S*)-Difluorphos was used. $[\alpha]_D^{21}$: +12.75 (*c* 1.1, CH_2Cl_2). IR (KBr): ν = 1693 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): δ = 2.38 (dd, *J* = 17.9 and 3.3 Hz, 1H), 2.88 (dd, *J* = 17.9 and 6.3 Hz, 1H), 3.27 (dd, *J* = 12.0 and 6.0 Hz 1H), 3.33–3.43 (m, 1H), 4.40 (t, *J* = 12.0 and 7.4 Hz, 1H), 4.60 (d, *J* = 16.8 Hz, 1H), 4.97 (d, *J* = 16.8 Hz, 1H), 7.62–7.67 (m, 4H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 40.5, 43.9, 66.4, 71.5, 125.7, 124.0 (q, *J* = 272 Hz), 125.6 (q, *J* = 3.8 Hz), 128.9, 130.0 (q, *J* = 33 Hz), 134.5, 134.6, 170.8, 171.6, 181.2, 206.8; HR-MS (EI+): *m/z* calcd. for $C_{14}H_{11}F_3O_2$: 268.0711; found: 268.0723.

Acknowledgements

NJ thanks KOSEF for the financial support through CMDS and grant No. R01-2007-006-10543-0. CC and DK are grateful to BK21 program (2004–2005) for the fellowship.

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[12] All molecular geometries incorporating diphosphine ligands [free L*, $PdCl_2$(L*) and Rh(CO)Cl(L*) complexes] were optimized with the same molecular mechanics program (CAChe Worksystem Pro 5.0), using the same parameter set: force field parameters, MM2; calculation type, structure optimization; optimisation method, conjugate gradient for no more than 3 000 updates or until convergence to 10^{-4} kcal. mol^{-1}.

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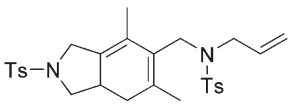
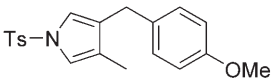
[14] Undesired side products were often obtained as an inseparable mixture of compounds derived from diene **3** (see Scheme 3). In case of reaction with **1a-1** and **1a-b**, analytically pure products were obtained; **10** and **11** were obtained from **1a-1** and **1a-2** as side products, respectively.



10



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