Available online at www.sciencedirect.com

SCIENCE DIRECT®

Tetrahedron 61 (2005) 9974–9979

Tetrahedron

Iridium-catalyzed enantioselective Pauson–Khand-type reaction of 1,6-enynes

Takanori Shibata,[a,*] Natsuko Toshida,[b] Mitsunori Yamasaki,[b] Shunsuke Maekawa[a] and Kentaro Takagi[b]

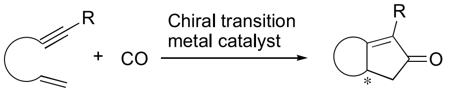
[a]*Department of Chemistry, School of Science and Engineering, Waseda University, Shinjuku, Tokyo 169-8555, Japan*
[b]*Department of Chemistry, Faculty of Science, Okayama University, Tsushima, Okayama 700-8530, Japan*

Received 7 July 2005; revised 4 August 2005; accepted 4 August 2005

Abstract—Iridium–chiral diphosphine complex catalyzes an enantioselective intramolecular Pauson–Khand-type reaction to give various chiral bicyclic cyclopentenones. The enantioselective reaction proceeds more smoothly and enantioselectively under a lower partial pressure of carbon monoxide. Moreover, aldehyde can be used as a CO source in the enantioselective carbonylative coupling.

1. Introduction

The Pauson–Khand reaction is a carbonylative coupling of alkyne and alkene, which was originally reported using a stoichiometric amount of a cobalt carbonyl complex in 1973.[1] The reaction gives synthetically useful cyclopentenones; in fact, it has been used as a key reaction in natural product syntheses.[2] In the 1990s, efforts were extended toward developing a catalytic reaction, and Jeong reported a practical intramolecular reaction of enynes using a cobalt–phosphite complex;[3] many publications on catalytic reaction conditions followed.[4] Further progress was made by reactions using other transition metal complexes as catalysts, known as a Pauson–Khand-type reaction.[5] Since Buchwald reported Ti-catalyzed intramolecular reaction of enynes,[6] Ru[7] and Rh complexes[8] were found to be efficient catalysts. The first catalytic and enantioselective Pauson–Khand-type reaction was also realized by Buchwald using a chiral titanium complex, where various enynes were transformed into the corresponding chiral bicyclic cyclopentenones in high ee.[9] Further achievements include enantioselective reactions using a cobalt complex by Hiroi,[10] a rhodium one by Jeong[11] and an iridium one by us[12] in 2000 (Eq. 1), and the development of an enantioselective Pauson–Khand-type reaction is still an intriguing topic these days.[13]



(1)

This manuscript discloses further investigation of an iridium-catalyzed enantioselective Pauson–Khand-type reaction. Various types of enynes were submitted to the reaction under an atmospheric pressure or a lower partial pressure of carbon monoxide.[14] Moreover, an iridium-catalyzed Pauson–Khand-type reaction using an aldehyde as a CO source is also presented.

2. Results and discussion

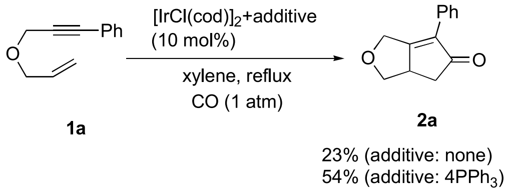
2.1. Iridium complex-catalyzed enantioselective coupling with carbon monoxide

In order to investigate the catalytic activity of an iridium complex, we first examined an intramolecular Pauson–Khand-type reaction of enyne **1a** (Eq. 2). The iridium complex, possessing triphenylphosphine as an achiral ligand, operated as a more efficient catalyst than that without phosphine ligands. The results were opposite to those of a rhodium complex-catalyzed reaction, where the addition of triphenylphosphine deactivated the catalytic activity,[8c] and they prompted us to examine chiral ligands for iridium-catalyzed enantioselective intramolecular Pauson–Khand-type reaction.

Keywords: Iridium; Enynes; Carbonylation; Pauson–Khand reaction; Enantioselective.

* Corresponding author. Tel./fax: +81 3 5286 8098;
e-mail: tshibata@waseda.jp

0040–4020/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2005.08.016

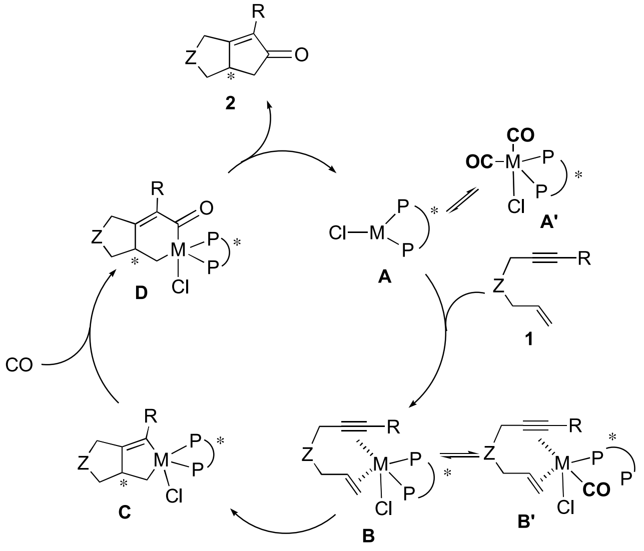


(2)

Next we investigated chiral diphosphines as chiral ligands (Table 1); with the increase of yield, enantioselectivity was improved and tolBINAP was found to be best among them. A good yield of 83% and high ee of 93% were achieved[15] (entries 1–5). Decreasing the amounts of catalyst to 5 mol% gave slightly poorer yield and enantioselectivity; however, drastic decrease of ee was observed, and a considerable amount of enyne **1** was recovered by 2 mol% catalyst (entries 6, 7). In order to increase the catalytic efficiency, the concentration of the chiral catalyst was found to be important: the higher yield and the same ee were achieved using 2 mol% catalyst when the reaction was examined for longer reaction time under the same concentration as that of entry 5 (entries 8, 9).

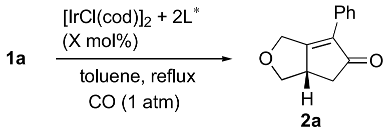
Various 1,6-enynes were submitted to the reaction using the chiral iridium catalyst,[16] which was prepared in situ from $[IrCl(cod)]_2$ and tolBINAP (Table 2). Electron-donating and -withdrawing substituents on the phenyl ring produced almost no effect, and the corresponding bicyclic enones **2b**,**c** were obtained in good yield with high ee (entries 1, 2). In place of aryl groups on the alkyne terminus of enyne, an isopropenyl group could be possible, yet with moderate yield (entry 3). Enynes, having alkyl groups on their alkyne termini, were also good substrates, and methyl-substituted enyne **1e** gave enone **2e** in the highest ee of 98% (entries 4–6). Not only oxygen-bridged enynes but also nitrogen-bridged enyne **1g** was enantiomerically transformed into bicyclic compound **2g** (entry 7); however, carbon-bridged enyne **1h** gave carbonylative product **2h** in moderate yield even over longer reaction time, and a considerable amount of enyne **1h** was recovered (entry 8). Decreasing a partial pressure of carbon monoxide accelerated the carbonylative coupling also in an iridium-catalyzed system,[8c] and higher yield was achieved under a 0.2 partial pressure of carbon monoxide without any lowering of ee.[17] Longer reaction time realized further better yield of ca. 90% (entries 9, 10). Also in the case of enyne **1i**, possessing a functionalized substituent on its alkyne terminus, decrease of a partial pressure of carbon monoxide worked well; moreover, ee was also significantly improved (entries 11, 12). Enyne, having 1,1-disubstituted olefin as an alkene moiety, is known to be rather inactive, and considerable amounts of enynes **1j**,**k** were recovered, respectively, under an atmospheric pressure of carbon monoxide (entries 13, 15). Due to the decrease of the partial pressure of CO, bicyclic cyclopentenones **2j**,**k**, having a chiral quaternary carbon, were obtained in acceptable yield and ee (entries 14, 16).

Scheme 1 depicts a possible mechanism: π-complexation of enyne **1** to chiral catalyst **A** induces an oxidative coupling to give metallacyclopentene **C**, where a chiral carbon is generated. Carbonyl insertion to **C** gives acyl complex **D**,[18] and the following reductive elimination provides enone **2** with regeneration of the active iridium species. In the reaction mixture, the mole amount of CO is much larger than that of the catalyst, which means that complex **A′** and **B′** could also exist by CO coordination. Complex **A′** is less reactive than **A**, and an oxidative coupling of **B′** lowers enantioselectivity. When the coupling is done under a lower



Scheme 1. A possible explanation for the effect of a partial pressure of CO.

Table 1. Investigation of chiral ligands and amounts of catalyst in iridium-catalyzed enantioselective Pauson–Khand-type reaction

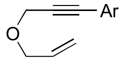
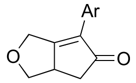
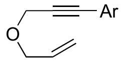
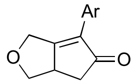
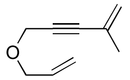
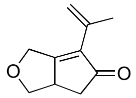
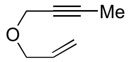
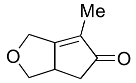
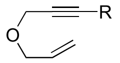
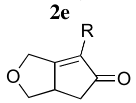
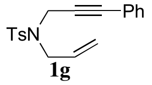
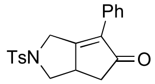
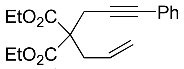
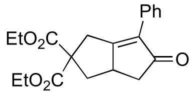
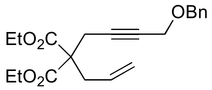
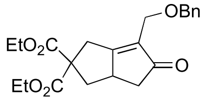
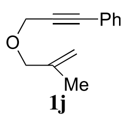
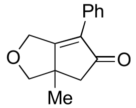
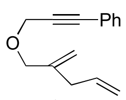
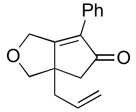


Entry	X	Chiral ligand[a]	[M]/mM[b]	Time/h	Yield/%	ee/%
1	10	CHIRAPHOS	15	12	13	<1
2	10	BDPP	15	12	23	22
3	10	DIOP	15	12	53	17
4	10	BINAP	15	12	64	86
5	10	tolBINAP	15	12	83	93
6	5	tolBINAP	7.5	24	75	91
7	2	tolBINAP	3	48	33	74
8	2	tolBINAP	15	48	59	93
9	2	tolBINAP	15	72	88	92

[a] (*S*,*S*)-isomers were used for entries 1–3. (*S*)-isomers were used for entries 4–10.

[b] Concentration of catalyst.

Table 2. Enantioselective Pauson–Khand-type reaction of various enynes under a CO atmosphere

Entry[a]	Enyne	Cyclopentenone	CO/atm	Time/h	Yield/%	ee/%
1	 Ar= 4-MeOPh **1b**	 **2b**	1.0	20	80	96
2	 Ar= 4-ClPh **1c**	 **2c**	1.0	20	78	95
3	 **1d**	 **2d**	1.0	20	54	97
4	 **1e**	 **2e**	1.0	20	60	98
5			1.0	48	75	97
6	 R= Ph(CH$_2$)$_3$ **1f**	 **2f**	1.0	20	54	90
7	 **1g**	 **2g**	1.0	12	85	95
8	 **1h**	 **2h**	1.0	36	51	88
9			0.2[b]	36	71	85
10			0.2[b]	72	89	86
11	 **1i**	 **2i**	1.0	72	15	84
12			0.2[b]	72	50	88
13	 **1j**	 **2j**	1.0	24	30	88
14			0.2[b]	72	86	93
15	 **1k**	 **2k**	1.0	96	22	86
16			0.2[b]	96	62	94

[a] [IrCl(cod)]$_2$+2(*S*)-tolBINAP (10 mol%), toluene, reflux.

[b] CO (0.2 atm) + Ar (0.8 atm).

partial pressure of CO, the content of **A** and **B** increases as compared with that of **A**′ and **B**′, which probably brings about the acceleration of the coupling and the increase of ee.[19]

Table 2 shows wide generality of the present iridium-catalyzed enantioselective Pauson–Khand-type reaction; however, there is a limitation of enynes (Fig. 1): under the same reaction conditions as Table 2, enynes, containing 1,2-disubstituted olefin as an alkene moiety, a 1,7-enyne, and enynes with no substituent on the alkyne terminus met with failure, and only a trace amount of or no carbonylated product was detected.

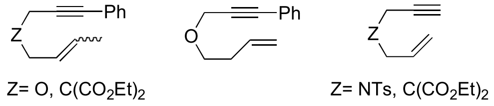
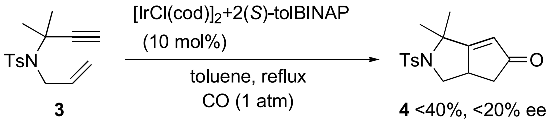


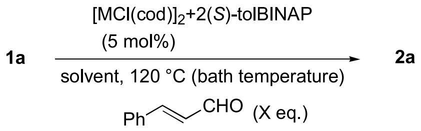
Figure 1. Enynes, which did not give carbonylated products.

We further examined enyne **3**, having no substituent on the alkyne terminus and having two methyls at the propargylic position, which deter isomerization of alkyne moiety to vinylidene complex.[20] Enone **4** was obtained yet only with low ee (Eq. 3). This result implies that the substituent on the alkyne terminus plays a pivotal role for high enantioselectivity.



(3)

Table 3. Examination of enantioselective Pauson–Khand-type reaction using cinnamaldehyde as a CO source



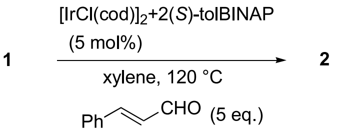
Entry	M	Solvent	*X*/equiv	Time/h	Yield/%	ee/%
1	Rh	None	20	5	89	82
2	Rh	Xylene	20	36	54	8
3	Ir	None	20	6	27	88
4	Ir	Xylene	20	12	52	86
5	Ir	Xylene	5	9	66	92
6	Ir	Toluene	5	24	25	95

2.2. Iridium complex-catalyzed enantioselective coupling using an aldehyde as a CO source

Recently, Morimoto and Kakiuchi[21] and we[22] independently reported a Rh-catalyzed Pauson–Khand-type reaction using aldehydes as a CO source in place of CO gas. Enantioselective reaction was also realized, where solvent-free condition is essential for high yield and ee (Table 3, entry 1).[22b] When the coupling was examined in xylene, it took much longer reaction time to consume enyne **1a** and enantioselectivity was extremely low (entry 2). We next examined an iridium-catalyzed coupling using an aldehyde as a CO source[23] and found that ee was high both with and without solvent; however, solvent was needed for high yield (entries 3, 4). Higher yield and ee were achieved by decreasing the amounts of cinnamaldehyde (entry 5). These results imply that the chiral rhodium complex would be stable and less reactive, and it works as a catalyst in harsh reaction conditions; on the contrary, the chiral iridium complex would be unstable, and solvent is needed for operating as an efficient catalyst.

Under the best reaction conditions (Table 3, entry 5), we examined an enantioselective coupling of several enynes (Table 4). In each entry, yield was moderate; however, ee was very high and exceeded that of rhodium-catalyzed coupling.[22b]

Table 4. Enantioselective Pauson–Khand-type reaction of various enynes using cinnamaldehyde as a CO source



Entry	Enyne	Time/h	Yield/%	ee/%
1	**1b**	5	57	91
2	**1c**	9	56	91
3	**1e**	24	30	85
4	**1g**	5	55	94
5	**1h**	24	51	87
6	**1j**	24	40	90

3. Conclusion

In summary, we have developed a catalytic and enantioselective Pauson–Khand-type reaction using a chiral iridium complex, which is readily prepared in situ from a commercially available and stable iridium complex and chiral diphosphine. Various enynes could be transformed into chiral bicyclic cyclopentenones in high ee. Especially, a low partial pressure of carbon monoxide facilitated the carbonylative coupling and improved the enantioselectivity. Furthermore, an enantioselective Pauson–Khand-type reaction using cinnamaldehyde as a CO source could be also achieved by chiral iridium complex and higher enantioselectivity was realized than that by the rhodium complex.

4. Experimental

4.1. General

Optical rotation was measured using Jasco DIP-370 polarimeter. IR spectra were recorded with Horiba FT210 spectrophotometer. NMR spectra were measured with JEOL AL-400 or Varian VXR-300S spectrometer using tetramethylsilane as an internal standard and $CDCl_3$ was used as solvent. Mass spectra were measured with JEOL JMS-SX102A and elemental analyses with Perkin Elmer PE2400II. Dehydrated toluene is commercially available and it was dried over molecular sieves 4 Å and degassed by carbon monoxide bubbling before use. All reactions were examined using a CO balloon or a balloon of CO and Ar (2:8). Spectral data of **2a**–**2c**, **2e**–**2h**, and **2j** were already published by others[4b,h,8b,c,9b,11,24,25] and us.[12,22]

4.2. Typical experimental procedure for enantioselective coupling with carbon monoxide (Table 2)

Preparation of a balloon with mixed gas of carbon monoxide and argon (2:8): CO (2 atm) was introduced into an autoclave (30 mL) then Ar (8 atm) was introduced into the autoclave; then the pressurized mixed gas (10 atm) was released into a balloon at an atmospheric pressure.

Under an atmosphere of carbon monoxide, tolBINAP (34.0 mg, 0.050 mmol) and $[Ir(cod)Cl]_2$ (16.8 mg, 0.025 mmol) were stirred in toluene (2.0 mL) at room temperature. After the addition of a toluene solution (2.0 mL) of enyne **1** (0.25 mmol), the reaction mixture was stirred under reflux for an appropriate time (cited in the table). The solvent was removed under reduced pressure, and the crude products were purified by thin-layer chromatography to give chiral cycloadduct **2**. Enantiomeric excess was determined by HPLC analysis using a chiral column.

4.2.1. 2-Isopropenyl-7-oxabicyclo[3.3.0]oct-1-en-3-one (2d). Pale yellow oil. IR (neat) 2852, 1712, 1651, 1456, 1028, 903 cm^{-1}; ^{1}H NMR $\delta=1.80$ (s, 3H), 2.22 (dd, $J=3.0$, 17.4 Hz, 1H), 2.72 (dd, $J=3.0$, 17.4 Hz, 1H), 3.21–3.25 (m, 2H), 4.33 (dd, $J=5.8$, 5.8 Hz, 1H), 4.63 (d, $J=16.6$ Hz, 1H), 4.77 (d, $J=16.6$ Hz, 1H), 5.21 (s, 1H), 5.61 (s, 1H); ^{13}C NMR $\delta=22.2$, 40.2, 43.3, 66.4, 71.4, 118.0, 134.6, 135.1, 176.5, 206.6; HRMS (EI$^+$) for M found *m*/*e* 164.0824, calcd for $C_{10}H_{12}O_2$: 164.0837. $[\alpha]_D^{31}$ -178.3 (*c* 1.17, CHCl$_3$, 97% ee). Enantiomeric excess was determined by HPLC analysis using a chiral column (Daicel Chiralpak AD-H: 4×250 mm, 254 nm UV detector, room temperature, eluent: 3% 2-propanol in hexane, flow rate: 1.0 mL/min, retention time: 15 min for major isomer and 16 min for minor isomer).

4.2.2. Diethyl 2-(benzyloxy)methyl-3-oxobicyclo[3.3.0]oct-1-en-7,7-dicarboxylate (2i). Pale yellow oil. IR (neat) 2982, 1730, 1672, 1267 cm^{-1}; ^{1}H NMR $\delta=1.21$–1.30 (m, 6H), 1.69 (dd, $J=12.7$, 12.7 Hz, 1H), 2.11 (dd, $J=3.3$, 17.9 Hz, 1H), 2.64 (dd, $J=6.2$, 17.9 Hz, 1H), 2.78 (dd, $J=7.7$, 12.7 Hz, 1H), 2.98–3.06 (m, 1H), 3.34 (d, $J=20.6$ Hz, 1H), 3.42 (d, $J=20.6$ Hz, 1H), 4.19–4.24 (m, 6H), 4.53 (s, 2H), 7.25–7.34 (m, 5H); ^{13}C NMR $\delta=14.1$, 34.7, 38.8, 41.6, 43.5, 61.1, 61.9, 62.0, 63.1, 73.1, 127.5, 128.2 133.6, 137.8, 170.6, 171.3, 181.2, 207.4; HRMS (FAB) for M+1 found *m*/*e* 387.1811, calcd for $C_{22}H_{27}O_6$: 387.1808. $[\alpha]_D^{31}$ -48.2 (*c* 1.11, CHCl$_3$, 88% ee). Enantiomeric excess was determined by HPLC analysis using a chiral column (Daicel Chiralpak AS-H: 4×250 mm, 254 nm UV detector, room temperature, eluent: 10% 2-propanol in hexane, flow rate: 1.0 mL/min, retention time: 13 min for minor isomer and 17 min for major isomer).

4.2.3. 2-Phenyl-5-(2-propenyl)-7-oxabicyclo[3.3.0]oct-1-en-3-one (2k). IR (neat) 1711, 1021, 919, 764 cm^{-1}; ^{1}H NMR $\delta=2.25$ (dd, $J=6.6$, 13.5 Hz, 1H), 2.39 (d, $J=17.4$ Hz, 1H), 2.48 (dd, $J=8.1$, 13.5 Hz, 1H), 2.69 (d, $J=17.4$ Hz, 1H), 3.40 (d, $J=8.1$ Hz, 1H), 4.14 (d, $J=8.1$ Hz, 1H), 4.58 (d, $J=16.4$ Hz, 1H), 4.93 (d, $J=16.4$ Hz, 1H), 5.12 (d, $J=0.9$ Hz, 1H), 5.16 (d, $J=4.5$ Hz, 1H), 5.59–5.77 (m, 1H), 7.32–7.51 (m, 5H); HRMS (EI$^+$) for M found *m*/*e* 240.1160, calcd for $C_{16}H_{16}O_2$: 240.1150. $[\alpha]_D^{23}$ $+5.28$ (c 0.56, CHCl$_3$, 94% ee). Enantiomeric excess was determined by HPLC analysis using a chiral column (Daicel Chiralpak AD-H: 4×250 nm, 254 nm UV detecter, room temperature, eluent: 10% 2-propanol in hexane, flow rate: 1.0 mL/min, retention time: 8 min for minor isomer and 10 min for major isomer).

4.3. Typical experimental procedure for enantioselective coupling using cinnamaldehyde as a CO source (Table 4)

Under an atmosphere of argon, tolBINAP (20.4 mg, 0.030 mmol) and [Ir(cod)Cl]$_2$ (10.1 mg, 0.015 mmol) were stirred in xylene (1.5 mL) at room temperature. After the addition of a xylene solution (0.5 mL) of enyne **1** (0.30 mmol) and cinnamaldehyde (198.0 mg, 1.5 mmol), the reaction mixture was stirred at 120 °C for an appropriate time (cited in the table). After the exclusion of excess cinnamaldehyde and xylene, the crude products were purified by thin-layer chromatography, and pure bicyclic enone **2** was obtained. Enantiomeric excess was determined by HPLC analysis using a chiral column.

Acknowledgements

This research was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology, Japan. We thank Prof. Koichi Narasaka and Dr. Yuji Koga (University of Tokyo) for helpful discussion. T. S. thanks the Inamori Foundation for supporting this work.

References and notes

1. (a) Khand, I. U.; Knox, G. R.; Pauson, P. L.; Watts, W. E. *J. Chem. Soc., Perkin Trans. 1* **1973**, 977–981. (b) Khand, I. U.; Pauson, P. L. *J. Chem. Soc., Perkin Trans. 1* **1976**, 30–32.
2. (a) Harrington, P. J. In *Transition Metals in Total Synthesis*; Wiley: New York, 1990, pp 259–301. (b) Blanco-Urgoiti, J.; Añorbe, L.; Pérez-Serrano, L.; Domínguez, G.; Pérez-Castells, J. *Chem. Soc. Rev.* **2004**, *33*, 32–42.
3. Jeong, N.; Hwang, S. H.; Lee, Y.; Chung, Y. K. *J. Am. Chem. Soc.* **1994**, *116*, 3159–3160.
4. (a) Lee, B. Y.; Chung, Y. K.; Lee, Y.; Hwang, S. H. *J. Am. Chem. Soc.* **1994**, *116*, 8793–8794. (b) Pagenkopf, B. L.; Livinghouse, T. *J. Am. Chem. Soc.* **1996**, *118*, 2285–2286. (c) Lee, N. Y.; Chung, Y. K. *Tetrahedron Lett.* **1996**, *37*, 3145–3148. (d) Jeong, N.; Hwang, S. H.; Lee, Y. W.; Lim, J. S. *J. Am. Chem. Soc.* **1997**, *119*, 10549–10550. (e) Kim, J. W.; Chung, Y. K. *Synthesis* **1998**, 142–144. (f) Belanger, D. B.; O'Mahony, D. J. R.; Livinghouse, T. *Tetrahedron Lett.* **1998**, *39*, 7637–7640. (g) Belanger, D. B.; Livinghouse, T. *Tetrahedron Lett.* **1998**, *39*, 7641–7644. (h) Sugihara, T.; Yamaguchi, M. *J. Am. Chem. Soc.* **1998**, *120*, 10782–10783. (i) Sugihara, T.; Yamaguchi, M. *Synlett* **1998**, 1384–1386. (j) Hayashi, M.; Hashimoto, Y.; Yamamoto, Y.; Usuki, J.; Saigo, K. *Angew. Chem., Int. Ed.* **2000**, *39*, 631–633.
5. (a) Geis, O.; Schmalz, H.-G. *Angew. Chem., Int. Ed.* **1998**, *37*, 911–914. (b) Jeong, N. In Beller, M, Bolm, C., Eds.; Transition Metals In Organic Synthesis; Wiley-VCH: Weinheim, 1998; Vol. 1, pp 560–577. (c) Chung, Y. K. *Coord. Chem. Rev.* **1999**, *188*, 297–341. (d) Hanson, B. E. *Comments Inorg. Chem.* **2002**, *23*, 289–318. (e) Gibson, S. E.; Stevenazzi, A. *Angew. Chem., Int. Ed.* **2003**, *42*, 1800–1810. (f) Park, K. H.; Chung, Y. K. *Synlett* **2005**, 545–559.
6. (a) Hicks, F. A.; Kablaoui, N. M.; Buchwald, S. L. *J. Am. Chem. Soc.* **1996**, *118*, 9450–9451. (b) Hicks, F. A.; Kablaoui, N. M.; Buchwald, S. L. *J. Am. Chem. Soc.* **1999**, *121*, 5881–5898.
7. (a) Morimoto, T.; Chatani, N.; Fukumoto, Y.; Murai, S. *J. Org. Chem.* **1997**, *62*, 3762–3765. (b) Kondo, T.; Suzuki, N.; Okada, T.; Mitsudo, T. *J. Am. Chem. Soc.* **1997**, *119*, 6187–6188.
8. (a) Koga, Y.; Kobayashi, T.; Narasaka, K. *Chem. Lett.* **1998**, 249–250. (b) Jeong, N.; Lee, S.; Sung, B. K. *Organometallics*

1998, *17*, 3642–3644. (c) Kobayashi, T.; Koga, Y.; Narasaka, K. *J. Organomet. Chem.* **2001**, *624*, 73–87.

9. (a) Hicks, F. A.; Buchwald, S. L. *J. Am. Chem. Soc.* **1996**, *118*, 11688–11689. (b) Hicks, F. A.; Buchwald, S. L. *J. Am. Chem. Soc.* **1999**, *121*, 7026–7033. (c) Sturla, S. J.; Buchwald, S. L. *J. Org. Chem.* **1999**, *64*, 5547–5550.
10. (a) Hiroi, K.; Watanabe, T.; Kawagishi, R.; Abe, I. *Tetrahedron Lett.* **2000**, *41*, 891–894. (b) Hiroi, K.; Watanabe, T.; Kawagishi, R.; Abe, I. *Tetrahedron: Asymmetry* **2000**, *11*, 797–808.
11. Jeong, N.; Sung, B. K.; Choi, Y. K. *J. Am. Chem. Soc.* **2000**, *122*, 6771–6772.
12. Shibata, T.; Takagi, K. *J. Am. Chem. Soc.* **2000**, *122*, 9852–9853.
13. (a) Sturla, S. J.; Buchwald, S. L. *J. Org. Chem.* **2002**, *67*, 3398–3403. (b) Suh, W. H.; Choi, M.; Lee, S. I.; Chung, Y. K. *Synthesis* **2003**, 2169–2172. (c) Jeong, N.; Kim, D. H.; Choi, J. H. *Chem. Commun.* **2004**, 1134–1135. (d) Gibson, S. E.; Lewis, S. E.; Loch, J. A.; Steed, J. W.; Tozer, M. J. *Organometallics* **2003**, *22*, 5382–5384. (e) Schmid, T. M.; Consiglio, G. *Tetrahedron: Asymmetry* **2004**, *15*, 2205–2208. (f) Fuji, K.; Morimoto, T.; Tsutsumi, K.; Kakiuchi, K. *Tetrahedron Lett.* **2004**, *45*, 9163–9166. (g) Gibson, S. E.; Kaufmann, K. A.; Loch, J. A.; Steed, J. W.; White, A. J. P. *Chem. Eur. J.* **2005**, *11*, 2566–2576. (h) Fan, B.-M.; Xie, J.-H.; Li, S.; Tu, Y.-Q.; Zhou, Q.-L. *Adv. Synth. Catal.* **2005**, *347*, 759–762. (i) Kwong, F. Y.; Li, Y. M.; Lam, W. H.; Qiu, L.; Lee, H. W.; Yeung, C. H.; Chan, K. S.; Chan, A. S. C. *Chem. Eur. J.* **2005**, *11*, 3872–3880.
14. Iridium-catalyzed Pauson–Khand-type reaction of allenynes: Shibata, T.; Kadowaki, S.; Hirase, M.; Takagi, K. *Synlett* **2003**, 573–575.
15. Absolute configuration of enone **2a** was determined by comparison with the sign of optical rotation in the literature (Ref. 9b).
16. Ir-tolBINAP complex could not be isolated and fully characterized, however, IrCl(cod)(tolBINAP) would be in situ formed as a pre-catalyst: Shibata, T.; Yamashita, K.; Ishida, H.; Takagi, K. *Org. Lett.* **2001**, *3*, 1217–1219.
17. Further lower partial pressure of CO (0.1 atm) gave a poorer yield along with the formation of non-carbonylated by-products. These results imply that a proper partial pressure would be needed for an efficient carbonyl insertion.
18. The carbonyl insertion between metal and sp^2-carbon was ascertained by characterization of acyl metal intermediate in iron carbonyl complex-mediated Pauson–Khand-type reaction of an allenyne: Shibata, T.; Koga, Y.; Narasaka, K. *Bull. Chem. Soc. Jpn.* **1995**, *68*, 911–919.
19. A cationic iridium complex, which was in situ prepared from $[\mathrm{IrCl(cod)}]_2$, tolBINAP, and AgOTf in 1,4-dioxane, was examined as a chiral catalyst for enyne **1a**, but a complex mixture was obtained.
20. Höhn, A.; Werner, H. *J. Organomet. Chem.* **1990**, *382*, 255–272.
21. (a) Morimoto, T.; Fuji, K.; Kakiuchi, K. *J. Am. Chem. Soc.* **2002**, *124*, 3806–3807. (b) Fuji, K.; Morimoto, T.; Tsutsumi, K.; Kakiuchi, K. *Angew. Chem., Int. Ed.* **2003**, *42*, 2409–2411.
22. (a) Shibata, T.; Toshida, N.; Takagi, K. *Org. Lett.* **2002**, *4*, 1619–1621. (b) Shibata, T.; Toshida, N.; Takagi, K. *J. Org. Chem.* **2002**, *67*, 7446–7450.
23. Iridium-catalyzed carbonylation using an aldehyde as a CO source: Simonato, J.-P.; Walter, T.; Métivier, P. *J. Mol. Catal. A* **2001**, *171*, 91–94.
24. Zhang, M.; Buchwald, S. L. *J. Org. Chem.* **1996**, *61*, 4498–4499.
25. Berk, S. C.; Grossmann, R. B.; Buchwald, S. L. *J. Am. Chem. Soc.* **1994**, *116*, 8593–8601.