Asymmetric Catalysis

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Highly Regio-, Diastereo-, and Enantioselective [2+2+2] Cycloaddition of 1,6-Enynes with Electron-Deficient Ketones Catalyzed by a Cationic Rh^I/H_8-binap Complex**

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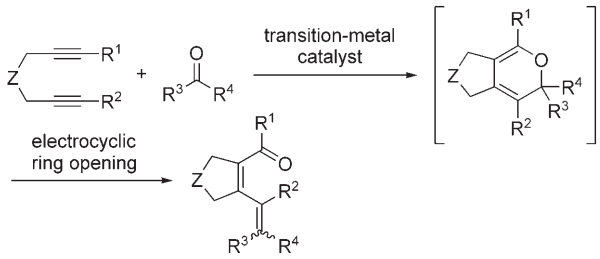
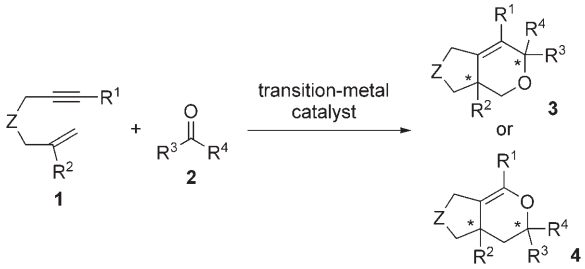
Transition-metal-catalyzed [2+2+2] cycloaddition reactions are efficient methods for the construction of six-membered carbocycles and heterocycles.[1] For the synthesis of six-membered oxygen heterocycles, [2+2+2] cycloaddition reactions involving carbonyl compounds are potentially attractive. Catalytic [2+2+2] cycloaddition reactions of diynes with carbonyl compounds[2] in the presence of various transition-metal complexes have been reported, for example, with Ni,[3] Ru,[4] and Rh.[5] However, these reactions frequently failed to produce oxygen heterocycles, and instead dienones were obtained as the major products as a result of electrocyclic ring opening of the initially formed fused α-pyrans (Scheme 1). In



Scheme 1. Transition-metal-catalyzed [2+2+2] cycloaddition of 1,6-diynes with carbonyl compounds.

contrast, a transition-metal-catalyzed [2+2+2] cycloaddition of enynes **1** to ketones **2** would furnish fused dihydropyrans **3** or **4** with two quaternary carbon centers,[6] bicyclic compounds that would not be converted into ring-opened products (Scheme 2). Although a Ni^0/imidazolylidene-catalyzed reaction of a 1,7-enyne with benzaldehyde has been reported, poor regioselectivity and β-hydride elimination



Scheme 2. Transition-metal-catalyzed [2+2+2] cycloaddition of 1,6-enynes with ketones.

prior to reductive elimination from the corresponding nickelacycle were observed.[3b,7] Our research group recently reported the reaction of 1,6-diynes with carbonyl compounds to give dienones and *ortho*-functionalized aryl ketones under the catalysis of cationic complexes of Rh^I with modified binap ligands (binap = 2,2′-bis(diphenylphosphanyl)-1,1′-binaphthyl).[8,9] Herein, we describe the [2+2+2] cycloaddition of 1,6-enynes with electron-deficient ketones to give fused dihydropyrans with two quaternary carbon centers under the catalysis of a cationic Rh^I/H_8-binap complex, as well as the *ortho* functionalization of aryl ketones with 1,6-enynes in the presence of the same catalyst. Both reactions proceed with excellent regio-, diastereo-, and enantioselectivity.

We first investigated the reaction of the tosylamide-linked 1,6-enyne **1a**, which contains a geminally disubstituted alkene moiety, with ethyl pyruvate (**2a**) in the presence of cationic Rh^I/binap-type bisphosphane complexes (Table 1). The reaction proceeded at 80 °C to give the desired fused dihydropyran **3aa** as a single regioisomer and a single diastereomer in excellent yield and with high enantioselectivity in the presence of the catalyst $[Rh(cod)_2]BF_4$/(*R*)-binap (10 mol %; Table 1, entry 1). The use of the sterically demanding binap-type bisphosphane ligands (*R*)-tol-binap and (*R*)-xyl-binap led to a significant decrease in the yield of **3aa** (Table 1, entries 2 and 3). Although the use of (*R*)-segphos led to an improvement in the enantioselectivity, the yield of **3aa** decreased to 58 % (Table 1, entry 4). Both high yield and high enantioselectivity were observed with the ligand (*R*)-H_8-binap (Table 1, entry 5).

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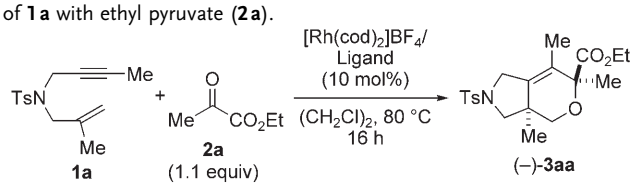
Table 1: Screening of ligands for the Rh-catalyzed [2+2+2] cycloaddition of **1a** with ethyl pyruvate (**2a**).



Entry	Ligand	Yield [%][a]	*ee* [%]
1	(*R*)-binap	>99	91
2	(*R*)-tol-binap[b]	22	92
3	(*R*)-xyl-binap[c]	<10	–
4	(*R*)-segphos[d]	58	96
5	(*R*)-H_8-binap[e]	>99	95

[a] Yield of the isolated product. [b] 2,2′-Bis(di-*p*-tolylphosphanyl)-1,1′-binaphthyl. [c] 2,2′-Bis(di(3,5-xylyl)phosphanyl)-1,1′-binaphthyl. [d] (4,4′-Bi-1,3-benzodioxole)-5,5′-diylbis(diphenylphosphane). [e] 2,2′-Bis(diphenylphosphanyl)-5,5′,6,6′,7,7′,8,8′-octahydro-1,1′-binaphthyl. cod = 1,5-cyclooctadiene, Ts = *p*-toluenesulfonyl.

We then explored the scope of this process with respect to the two substrates (Table 2). Not only ethyl pyruvate (**2a**; Table 2, entry 1), but also 2,3-butanedione (**2b**; entry 3) and diethyl ketomalonate (**2d**, entry 5), underwent the desired reaction with **1a** to furnish the expected dihydropyran in high yield; however, the reaction of ethyl phenylglyoxylate (**2c**) with **1a** gave the expected dihydropyran **3ac** in low yield (Table 2, entry 4), and acetone (**2e**) failed to react with **1a** (entry 6).[10] When the reaction of **1a** with **2a** was carried out at 25 °C with 20 mol % of the Rh catalyst, almost complete enantioselectivity was observed (Table 2, entry 2).

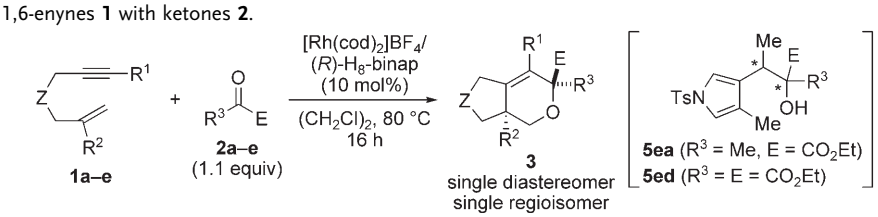
We found that 1,6-enynes with tosylamide (**1a**; Table 2, entries 1–5), malonate (**1b**, entries 7–9), and oxygen (**1c** and **1d**, entries 10–13) linkages could be used in the cycloaddition. With respect to the substituent R^1 at the alkyne terminus, 1,6-enynes substituted not only with methyl (**1a**; Table 2, entries 1–5), but also with phenyl and 4-bromophenyl groups (**1c** and **1b**, entries 7–11), participated in the reaction. In the case of the 4-bromophenyl-substituted 1,6-enyne **1b**, improved yield and enantioselectivity were observed when the reaction was carried out at 25 °C with 20 mol % of the Rh catalyst (Table 2, entry 9). The reaction of the methoxycarbonyl-substituted 1,6-enyne **1d** with **2a** furnished the corresponding dihydropyran **3da** in low yield as a result of the rapid [2+2+2] homocycloaddition of **1d** (Table 2, entry 12); however, when the highly electron deficient ketone **2d** was used, the corresponding dihydropyran **3dd** was obtained in good yield (entry 13). Although the 1,6-enyne **1e** with a monosubstituted alkene moiety reacted with **2a**, the alcohol **5ea** was obtained as the major product along with the expected dihydropyran **3ea** (Table 2, entry 14). Furthermore, the use of diethyl ketomalonate (**2d**) instead of **2a** led to the almost exclusive formation of the alcohol **5ed** (Table 2, entry 15).[11,12]

We applied this regio-, diastereo-, and enantioselective [2+2+2] cycloaddition to the synthesis of the enantiomerically enriched spirocyclic compound **3cf** by using 1-methylisatin (**2f**) as the carbonyl substrate (Scheme 3).[13] Importantly, neither the regioisomer **4** nor the other diastereomer was detected in the crude product mixture for this reaction or any of those described in Table 2. The absolute configuration of the dihydropyran product (−)-**3ab** was determined by the anomalous dispersion method (Figure 1.)[14]

Scheme 4 depicts a possible mechanism for the selective formation of the dihydropyran (3*R*,6*S*)-**3ab**: The 1,6-enyne **1a** reacts with the rhodium center of the catalyst to form the rhodacyclopentene **A** as a result of a steric interaction between the Rh-CH_2 moiety and the equatorial P-Ph group of (*R*)-H_8-binap. Subsequently, 2,3-butanedione (**2b**) coordinates to **A** to form complex **B**. The insertion of **2b** followed by the reductive elimination of rhodium then furnishes (3*R*,6*S*)-**3ab**.

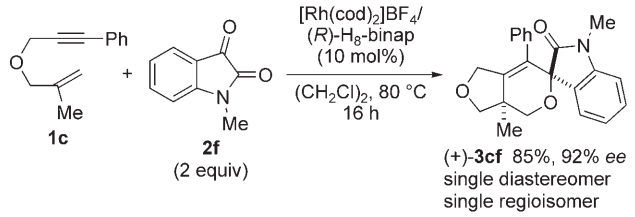
Next, we examined the reaction of 1,6-enynes with electron-rich aryl ketones (Table 3). In analogy with

Table 2: Rh^{I+}/(*R*)-H_8-binap-catalyzed regio-, diastereo-, and enantioselective [2+2+2] cycloaddition of 1,6-enynes **1** with ketones **2**.



Entry	**1** (Z, R^1, R^2)	**2** (R^3, E)	**3**	Yield [%][a]	*ee* [%]
1	**1a** (NTs, Me, Me)	**2a** (Me, CO_2Et)	(−)-**3aa**	>99	95
2[b,c]	**1a** (NTs, Me, Me)	**2a** (Me, CO_2Et)	(−)-**3aa**	91	>99
3	**1a** (NTs, Me, Me)	**2b** (Me, Ac)[d]	(3*R*,6*S*)-(−)-**3ab**[e]	73	98
4	**1a** (NTs, Me, Me)	**2c** (Ph, CO_2Et)	(+)-**3ac**	24	97
5	**1a** (NTs, Me, Me)	**2d** (CO_2Et, CO_2Et)	(−)-**3ad**	89	97
6	**1a** (NTs, Me, Me)	**2e** (Me, Me)[f]	**3ae**	<1	–
7	**1b** ($C(CO_2Me)_2$, Ar,[g] Me)	**2a** (Me, CO_2Et)	(+)-**3ba**	49	98
8	**1b** ($C(CO_2Me)_2$, Ar,[g] Me)	**2b** (Me, Ac)[d]	(+)-**3bb**	33	92
9[b,c]	**1b** ($C(CO_2Me)_2$, Ar,[g] Me)	**2a** (Me, CO_2Et)	(+)-**3ba**	82	>99
10	**1c** (O, Ph, Me)	**2a** (Me, CO_2Et)	(+)-**3ca**	67	>99
11	**1c** (O, Ph, Me)	**2d** (CO_2Et, CO_2Et)	(+)-**3cd**	64	96
12	**1d** (O, CO_2Me, Me)	**2a** (Me, CO_2Et)	(−)-**3da**	17	98
13	**1d** (O, CO_2Me, Me)	**2d** (CO_2Et, CO_2Et)	(−)-**3dd**	61	93
14[b,h]	**1e** (NTs, Me, H)	**2a** (Me, CO_2Et)[d]	(−)-**3ea**	25 (30[l])	94 (>99[i,j], 81[i,k])
15[b,h]	**1e** (NTs, Me, H)	**2d** (CO_2Et, CO_2Et)[d]	**3ed**	<1 (70[l])	– (52[l])

[a] Yield of the isolated product. [b] Catalyst: 20 mol %. [c] The reaction was carried out at 25 °C in CH_2Cl_2. [d] Compound **2**: 2 equivalents. [e] The absolute configuration of (−)-**3ab** was determined by X-ray crystallographic analysis (Figure 1). [f] Acetone (**2e**) was used as both substrate and solvent. [g] Ar = 4-BrC_6H_4. [h] Ligand: (*R*)-binap. [i] Data for **5ea** (d.r. 2.8:1). [j] The *ee* value of the major diastereomer. [k] The *ee* value of the minor diastereomer. [l] Data for **5ed**.



Scheme 3. Synthesis of the enantiomerically enriched spirocyclic compound (+)-**3cf**.

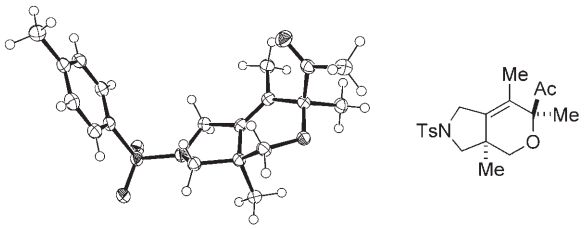
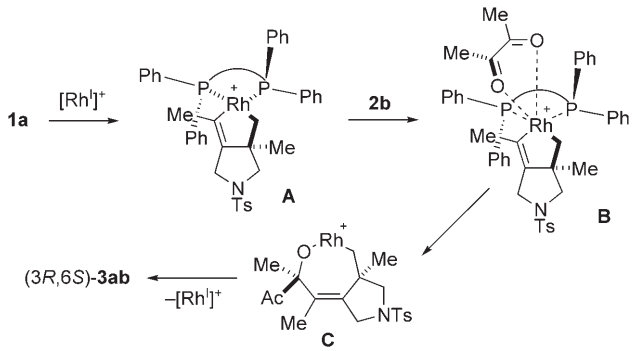


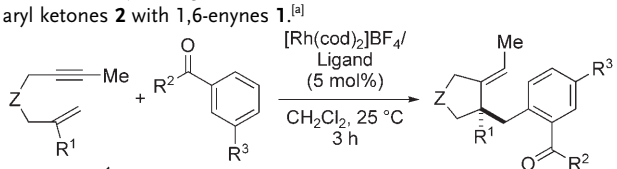
Figure 1. ORTEP drawing of (3*R*,6*S*)-(−)-**3ab** drawn at the 50% probability level.



Scheme 4. Possible mechanism for the selective formation of the dihydropyran (3*R*,6*S*)-**3ab**.

the reactions of 1,6-diynes with electron-rich aryl ketones,[8a] when the 1,6-enyne **1e** was added over 5 min to a solution of benzophenone (**2g**) and the $[Rh(cod)_2]BF_4$/(*R*)-H_8-binap catalyst (5 mol%) in CH_2Cl_2 at 25°C, the *ortho*-functionalized aryl ketone **6eg** was isolated in 55% yield (Table 3, entry 1).[15–17] Although the desired product was obtained in comparable yield when the ligand (*R*)-segphos was used (Table 3, entry 2), the use of (*R*)-binap led to a significantly lower yield of **6eg** (entry 3).[18] These reactions proceeded with perfect regioselectivity and high enantioselectivity. Acetophenone (**2h**) also participated in the reaction with **1e** (Table 3, entry 4). Although **2i**, in which the *meta* substituent R^3 is an electron-donating group, reacted with **1f** to provide the expected product **6fi** as a single regioisomer (Table 3, entry 5), the presence of an electron-withdrawing group at the *meta* position (in **2j**) led to a complete shutdown of the reaction (entry 6). Furthermore, the 1,6-enyne **1a** with a geminally disubstituted alkene moiety failed to react with **2g**. Instead, **1a** underwent [2+2+2] homocycloaddition (Table 3, entry 7). The absolute configuration of the *ortho*-

Table 3: Rh-catalyzed regio- and enantioselective *ortho* functionalization of aryl ketones **2** with 1,6-enynes **1**.[a]



1e (Z = NTs, R^1 = H)
1f (Z = $C(CO_2Et)_2$, R^1 = H)
1a (Z = NTs, R^1 = Me)
2g–j (10 equiv)
6

Entry	**1**	**2** (R^2, R^3)	Ligand	**6**	Yield [%][b]	*ee* [%]
1	**1e**	**2g** (Ph, H)	(*R*)-H_8-binap	(+)-**6eg**	55	96
2	**1e**	**2g** (Ph, H)	(*R*)-segphos	(+)-**6eg**	59	95
3	**1e**	**2g** (Ph, H)	(*R*)-binap	(+)-**6eg**	26	97
4	**1e**	**2h** (Me, H)	(*R*)-H_8-binap	(*R*)-(+)-**6eh**[c]	34	98
5	**1f**	**2i** (Me, OMe)	(*R*)-H_8-binap	(+)-**6fi**	34	94
6	**1f**	**2j** (Me, CF_3)	(*R*)-H_8-binap	**6fj**	<1	–
7	**1a**	**2g** (Ph, H)	(*R*)-H_8-binap	**6ag**	<1	–

[a] The enyne **1** was added over a period of 5 min (see the Supporting Information). [b] Yield of the isolated product. [c] The absolute configuration of (+)-**6eh** was determined by X-ray crystallographic analysis (Figure 2).

functionalized aryl ketone (+)-**6eh** was determined by the anomalous dispersion method (Figure 2).[14]

In conclusion, a cationic Rh^I/(*R*)-H_8-binap complex catalyzes the [2+2+2] cycloaddition of 1,6-enynes with

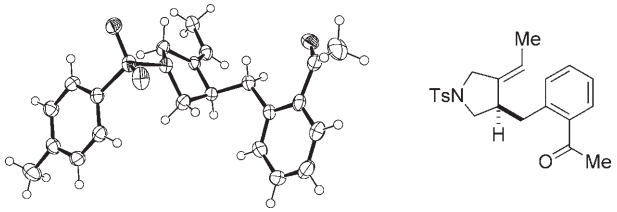


Figure 2. ORTEP drawing of (*R*)-(+)-**6eh** drawn at the 50% probability level.

electron-deficient ketones to give fused dihydropyrans containing two quaternary carbon centers with excellent regio-, diastereo-, and enantioselectivity. Electron-rich aryl ketones react with 1,6-enynes in the presence of the same catalyst to give *ortho*-functionalized aryl ketones with excellent regio- and enantioselectivity. Further studies to expand the scope of the two reactions and elucidate the reaction mechanisms are in progress.

Experimental Section

Representative procedure: (*R*)-H_8-binap (18.9 mg, 0.030 mmol) and $[Rh(cod)_2]BF_4$ (12.2 mg, 0.030 mmol) were dissolved in CH_2Cl_2 (2.0 mL) in a Schlenk tube under an argon atmosphere, and the

mixture was stirred at room temperature for 5 min. H_2 was introduced into the resulting solution, which was then stirred at room temperature for 0.5 h, concentrated to dryness, and dissolved in $(CH_2Cl)_2$ (0.5 mL). A solution of **1c** (55.9 mg, 0.300 mmol) and **2f** (96.7 mg, 0.600 mmol) in $(CH_2Cl)_2$ (1.5 mL) was added at room temperature, and the resulting mixture was stirred at 80 °C for 16 h. The reaction mixture was then concentrated, and the product was purified by preparative TLC (hexane/ethyl acetate 2:1) to furnish (+)-**3cf** (88.8 mg, 0.256 mmol, 85 %, 92 % *ee*, single diastereomer) as a pale yellow oil. $[\alpha]_D^{25} = +52.8\ deg\,cm^3\,g^{-1}\,dm^{-1}$ ($c = 2.04 \times 10^{-2}\ g\,cm^{-3}$ acetone; 92 % *ee*); ^1H NMR ($CDCl_3$, 300 MHz): $\delta = 7.29$ (d, $J = 7.5$ Hz, 1H), 7.20 (t, $J = 7.5$ Hz, 1H), 7.15–6.99 (m, 4H), 6.87–6.75 (m, 2H), 6.57 (d, $J = 7.5$ Hz, 1H), 4.59 (d, $J = 10.5$ Hz, 1H), 4.45 (d, $J = 13.8$ Hz, 1H), 4.09 (d, $J = 13.8$ Hz, 1H), 3.93 (d, $J = 10.5$ Hz, 1H), 3.91 (d, $J = 8.1$ Hz, 1H), 3.62 (d, $J = 8.1$ Hz, 1H), 3.00 (s, 3H), 1.58 ppm (s, 3H); ^{13}C NMR ($CDCl_3$, 75 MHz): $\delta = 175.6$, 144.3, 144.1, 135.3, 129.9, 128.7, 128.6, 128.0, 127.5, 127.2, 124.4, 122.9, 108.2, 79.1, 77.0, 69.7, 68.3, 41.4, 25.8, 23.0 ppm; IR (neat): $\tilde{\nu} = 2964$, 1715, 1090, 1052, 705 cm^{-1}; HRMS (FAB): *m*/*z* calcd for $C_{22}H_{21}NO_3$: 380.1532; found: 380.1562 $[M+H]^+$; HPLC (chiralcel OD-H, hexane/*i*PrOH 90:10, 1.0 mL min^{-1}): t_R(major isomer): 8.5 min, t_R(minor isomer): 12.9 min.

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[1] For recent reviews on [2+2+2] cycloaddition, see: a) B. Heller, M. Hapke, *Chem. Soc. Rev.* **2007**, *36*, 1085; b) P. R. Chopade, J. Louie, *Adv. Synth. Catal.* **2006**, *348*, 2307; c) V. Gandon, C. Aubert, M. Malacria, *Chem. Commun.* **2006**, 2209; d) S. Kotha, E. Brahmachary, K. Lahiri, *Eur. J. Org. Chem.* **2005**, 4741; e) Y. Yamamoto, *Curr. Org. Chem.* **2005**, *9*, 503; f) J. A. Varela, C. Saá, *Chem. Rev.* **2003**, *103*, 3787; g) N. Agenet, O. Buisine, F. Slowinski, V. Gondon, C. Aubert, M. Malacria, *Organic Reactions*, *Vol. 68* (Ed.: L. E. Overman), Wiley, Hoboken, **2007**, p. 1.

[2] For the use of stoichiometric Co reagents, see: a) D. F. Harvey, B. M. Johnson, C. S. Ung, K. P. C. Vollhardt, *Synlett* **1989**, 15; b) R. Gleiter, V. Schehlmann, *Tetrahedron Lett.* **1989**, *30*, 2893; for the use of stoichiometric zirconacyclopentadienes, see: c) T. Takahashi, Y. Li, T. Ito, F. Xu, K. Nakajima, Y. Liu, *J. Am. Chem. Soc.* **2002**, *124*, 1144.

[3] For pioneering work on Ni catalysis, see: a) T. Tsuda, T. Kiyoi, T. Miyane, T. Saegusa, *J. Am. Chem. Soc.* **1988**, *110*, 8570; for the use of Ni^0/imidazolylidene complexes, see: b) T. N. Tekevac, J. Louie, *Org. Lett.* **2005**, *7*, 4037; for the Ni-catalyzed [4+2+2] cycloaddition of 1,6-diynes with cyclobutanones, see: c) M. Murakami, S. Ashida, T. Matsuda, *J. Am. Chem. Soc.* **2006**, *128*, 2166.

[4] For pioneering work on Ru catalysis, see: a) Y. Yamamoto, H. Takagishi, K. Itoh, *J. Am. Chem. Soc.* **2002**, *124*, 6844; for the Ru^{II}-catalyzed hydrative cyclization and [4+2] cycloaddition of yne–enones, see: b) B. M. Trost, R. E. Brown, F. D. Toste, *J. Am. Chem. Soc.* **2000**, *122*, 5877.

[5] For the [{Rh(cod)Cl}$_2$]-catalyzed intramolecular [2+2+2] cycloaddition of diynals (cod = 1,5-cyclooctadiene), see: a) B. Bennacer, M. Fujiwara, S.-Y. Lee, I. Ojima, *J. Am. Chem. Soc.* **2005**, *127*, 17756; for a Rh^{I+}/biphep-catalyzed carbonyl *Z* dienylation involving carbonyl insertion into cationic rhodacyclopentadienes (biphep = 2,2′-bis(diphenylphosphanyl)-1,1′-biphenyl), see: b) J. R. Kong, M. J. Krische, *J. Am. Chem. Soc.* **2006**, *128*, 16040.

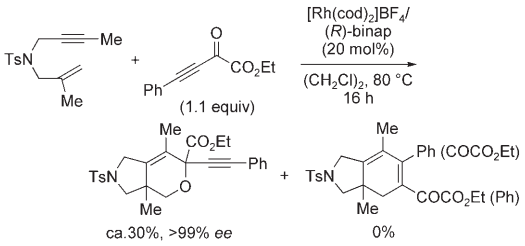
[6] For recent reviews of catalytic asymmetric methods for the generation of quaternary carbon centers, see: a) B. M. Trost, C. Jiang, *Synthesis* **2006**, 369; b) C. J. Douglas, L. E. Overman, *Proc. Natl. Acad. Sci. USA* **2004**, *101*, 5363; c) I. Denissova, L. Barriault, *Tetrahedron* **2003**, *59*, 10105.

[7] For the Au-catalyzed diastereoselective intermolecular addition of carbonyl compounds to 1,6-enynes to give fused [5,5] ring systems, see: M. Schelwies, A. L. Dempwolff, F. Rominger, G. Helmchen, *Angew. Chem.* **2007**, *119*, 5694; *Angew. Chem. Int. Ed.* **2007**, *46*, 5598.

[8] a) K. Tanaka, Y. Otake, A. Wada, K. Noguchi, M. Hirano, *Org. Lett.* **2007**, *9*, 2203; a similar publication appeared soon afterwards: b) K. Tsuchikama, Y. Yoshinami, T. Shibata, *Synlett* **2007**, 1395.

[9] For selected reports by our research group of [2+2+2] cycloaddition reactions of alkynes under the catalysis of cationic Rh^I/modified-binap complexes, see: a) K. Tanaka, K. Shirasaka, *Org. Lett.* **2003**, *5*, 4697; b) K. Tanaka, G. Nishida, A. Wada, K. Noguchi, *Angew. Chem.* **2004**, *116*, 6672; *Angew. Chem. Int. Ed.* **2004**, *43*, 6510; c) K. Tanaka, K. Toyoda, A. Wada, K. Shirasaka, M. Hirano, *Chem. Eur. J.* **2005**, *11*, 1145; d) K. Tanaka, K. Takeishi, K. Noguchi, *J. Am. Chem. Soc.* **2006**, *128*, 4586; e) K. Tanaka, H. Sagae, K. Toyoda, K. Noguchi, M. Hirano, *J. Am. Chem. Soc.* **2007**, *129*, 1522; f) G. Nishida, K. Noguchi, M. Hirano, K. Tanaka, *Angew. Chem.* **2007**, *119*, 4025; *Angew. Chem. Int. Ed.* **2007**, *46*, 3951, and references therein; for similar reactions of nitriles, see: g) K. Tanaka, N. Suzuki, G. Nishida, *Eur. J. Org. Chem.* **2006**, 3917; h) A. Wada, K. Noguchi, M. Hirano, K. Tanaka, *Org. Lett.* **2007**, *9*, 1295; for similar reactions of isocyanates and isothiocyanates, see: i) K. Tanaka, A. Wada, K. Noguchi, *Org. Lett.* **2005**, *7*, 4737; j) K. Tanaka, A. Wada, K. Noguchi, *Org. Lett.* **2006**, *8*, 907; for similar reactions of alkenes, see: k) K. Tanaka, G. Nishida, H. Sagae, M. Hirano, *Synlett* **2007**, 1426.

[10] We investigated the chemoselectivity of the present cycloaddition with respect to the reactivity of a carbonyl group in the presence of an alkyne moiety and found that the carbonyl group of an alkynyl ketoester reacted with a 1,6-enyne, although the cycloadduct could not be isolated in pure form. For the [2+2+2] cycloaddition of 1,6-enynes with monoalkynes under the catalysis of cationic complexes of Rh^I with modified binap ligands, see: a) P. A. Evans, K. W. Lai, J. R. Sawyer, *J. Am. Chem. Soc.* **2005**, *127*, 12466; b) T. Shibata, Y. Arai, Y. Tahara, *Org. Lett.* **2005**, *7*, 4955.



[11] When the ligand (*R*)-binap was used, the cycloaddition products were obtained in higher yields than with (*R*)-H_8-binap.

[12] Similar heterocycle formation during the transition-metal-catalyzed cycloisomerization of enynes was reported; for Ru, see: a) M. Mori, Y. Kozawa, M. Ishida, M. Kanamaru, K. Onozuka, M. Takimoto, *Org. Lett.* **2000**, *2*, 3245; for Co, see: b) O. Buisine, C. Aubert, M. Malacria, *Chem. Eur. J.* **2001**, *7*, 3517; for Rh, see: c) H. Kawai, S. Oi, Y. Inoue, *Heterocycles* **2006**, *67*, 101; d) K. Tanaka, Y. Otake, M. Hirano, *Org. Lett.* **2007**, *9*, 3953.

[13] For the synthesis of chiral spirocyclic compounds through a [2+2+2] cycloaddition catalyzed by a cationic Rh^I/modified-binap complex, see: K. Tsuchikama, Y. Kuwata, T. Shibata, *J. Am. Chem. Soc.* **2006**, *128*, 13686.

[14] CCDC-662606 (**3ab**) and CCDC-662607 (**6eh**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

[15] For the Rh- or Ir-catalyzed dienylation of aromatic C–H bonds with alkynes, see: a) M. C. Comstock, J. R. Shapley, *Organometallics* **1997**, *16*, 4816; b) J. Müller, T. Akhnoukh, P. Escarpa Gaede, A. Guo, P. Moran, K. Qiao, *J. Organomet. Chem.* **1997**, *541*, 207; c) S. A. Gardner, P. S. Andrews, M. D. Rausch, *Inorg. Chem.* **1973**, *12*, 2396.

[16] For the Co-mediated dienylation of aromatic C–H bonds with alkynes, see: a) C. Aubert, P. Betschmann, M. J. Eichberg, V. Gandon, T. J. Heckrodt, J. Lehmann, M. Malacria, B. Masjost, E. Paredes, K. P. C. Vollhardt, G. D. Whitener, *Chem. Eur. J.* **2007**, *13*, 7443; b) H. Pelissier, J. Rodriguez, K. P. C. Vollhardt, *Chem. Eur. J.* **1999**, *5*, 3549; c) R. Boese, D. F. Harvey, M. J. Malaska, K. P. C. Vollhardt, *J. Am. Chem. Soc.* **1994**, *116*, 11153; d) D. B. Grotjahn, K. P. C. Vollhardt, *J. Am. Chem. Soc.* **1986**, *108*, 2091; e) Y. Wakatsuki, H. Yamazaki, *J. Organomet. Chem.* **1978**, *149*, 385; f) H. Yamazaki, Y. Wakatsuki, *J. Organomet. Chem.* **1978**, *149*, 377; for theoretical studies, see: g) C. Aubert, V. Gandon, A. Geny, T. J. Heckrodt, M. Malacria, E. Paredes, K. P. C. Vollhardt, *Chem. Eur. J.* **2007**, *13*, 7466; h) V. Gandon, N. Agenet, K. P. C. Vollhardt, M. Malacria, C. Aubert, *J. Am. Chem. Soc.* **2006**, *128*, 8509.

[17] For selected examples of the Rh-catalyzed chelation-assisted intermolecular hydroarylation of alkynes and alkenes, see: a) J. C. Lewis, R. G. Bergman, J. A. Ellman, *J. Am. Chem. Soc.* **2007**, *129*, 5332; b) C.-H. Jun, C. W. Moon, J.-B. Hong, S.-G. Lim, K.-Y. Chung, Y.-H. Kim, *Chem. Eur. J.* **2002**, *8*, 485; c) C. P. Lenges, M. Brookhart, *J. Am. Chem. Soc.* **1999**, *121*, 6616; d) U. R. Aulwurm, J. U. Melchinger, H. Kisch, *Organometallics* **1995**, *14*, 3385, and references therein.

[18] Recently, the *ortho* functionalization of aryl ketones with 1,6-enynes in the presence of a cationic Rh^{I}/(*R*)-binap catalyst was reported. However, the use of (*R*)-binap required the very slow addition (over a period of 30 min) of the enyne substrate; furthermore, neither the absolute configuration of the product nor electronic effects on the reaction were determined: K. Tsuchikama, Y. Kuwata, Y. Tahara, Y. Yoshinami, T. Shibata, *Org. Lett.* **2007**, *9*, 3097.

