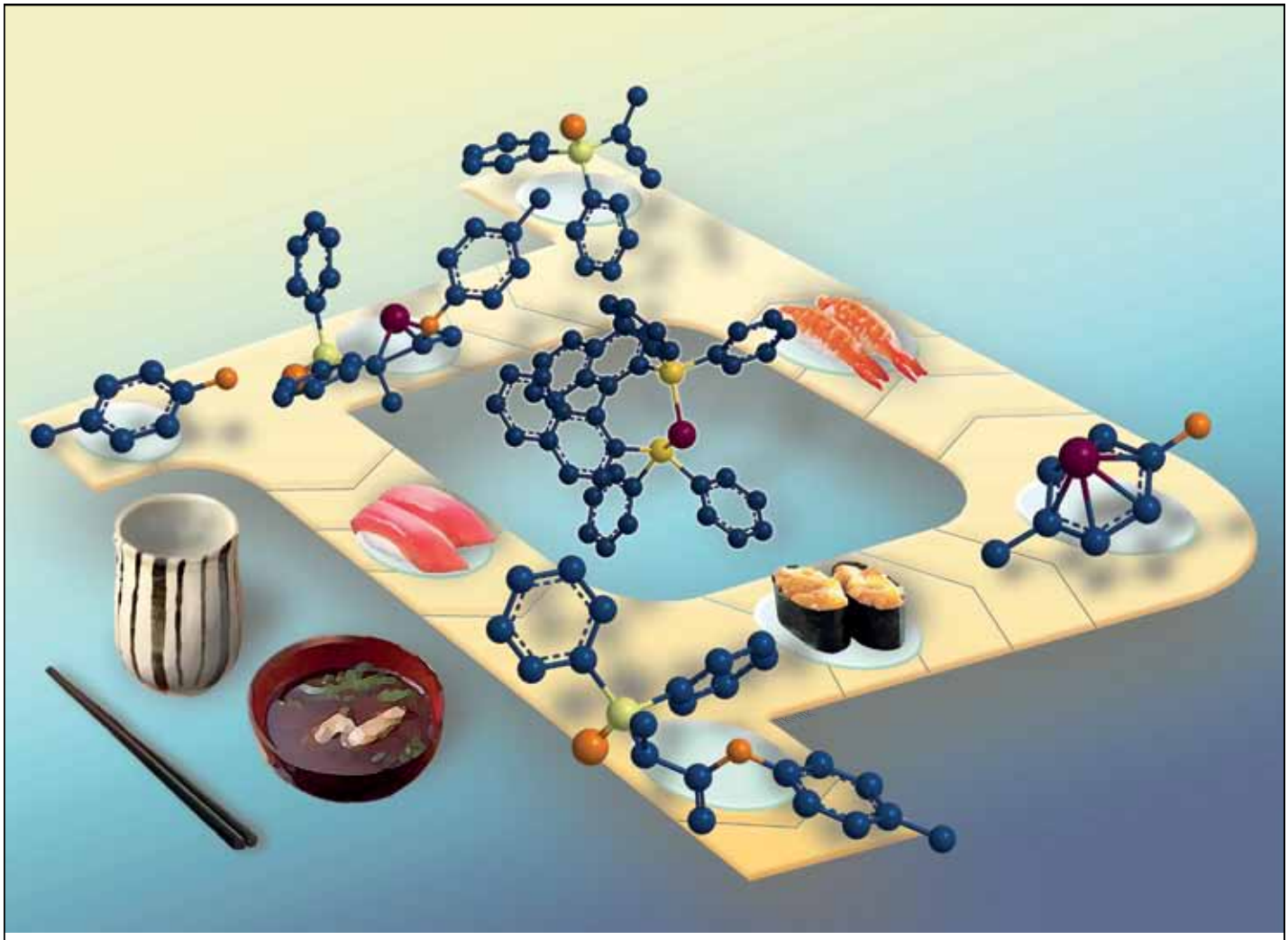

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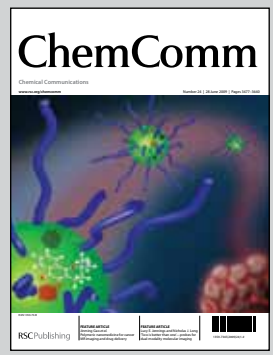

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Rhodium-catalyzed asymmetric hydroalkoxylation and hydrosulfenylation of diphenylphosphinylallenes†‡

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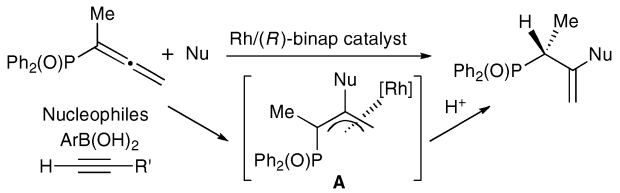
The rhodium-catalyzed intermolecular asymmetric hydroalkoxylation and hydrosulfenylation of diphenylphosphinylallenes gave chiral allylic phosphine oxides substituted with vinyl ether and thioether moieties in high yields with high enantioselectivities.

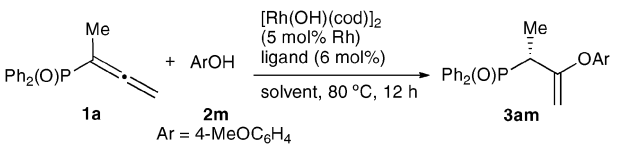
The catalytic addition of a hydrogen–oxygen bond to an unsaturated carbon–carbon bond, hydroalkoxylation, is a simple and atom-economical route to construct carbon–oxygen bonds, and its asymmetric variant is of great value to provide useful chiral compounds. As one of the asymmetric hydroalkoxylations, oxa-Michael-type addition to electron-deficient olefins has recently been developed under organic and Lewis acid catalysis.[1] On the other hand, despite the recent progress of hydroalkoxylation based on transition metal catalysts,[2,3] there are only a few examples of asymmetric hydroalkoxylation. For example, the gold-catalyzed asymmetric intramolecular hydroalkoxylation of allenes for the synthesis of chiral oxygen heterocycles was reported independently by Zhang and Widenhoefer,[4] and Toste *et al.*[5] The palladium-catalyzed asymmetric intramolecular hydroalkoxylation of alkynes reported by Yamamoto *et al.* was proposed to proceed *via in situ*-generated allenes.[6] Meanwhile, there have been no reports on the intermolecular asymmetric hydroalkoxylation of allenes, to the best of our knowledge. Recently, we reported the rhodium-catalyzed asymmetric hydroarylation[7] and hydroalkynylation[8] of diphenylphosphinylallenes,[9] where a π-allylrhodium species **A** is formed as a key intermediate, and the following regioselective protonation determines the enantioselectivity (Scheme 1). In this context, we focused on oxygen nucleophiles for the asymmetric addition to allenes, giving chiral vinyl ethers. Here, we report the rhodium-catalyzed asymmetric addition of phenols to diphenylphosphinylallenes. The results of asymmetric hydrosulfenylation are also reported.

Our initial studies were focused on the asymmetric addition of *p*-methoxyphenol (**2m**) to 3-(diphenylphosphinyl)-1,2-butadiene (**1a**) to give chiral vinyl ether **3am** in the presence of a hydroxorhodium complex coordinated with a chiral bisphosphine ligand (Table 1). Treatment of allene **1a** with phenol **2m** (1 equiv.) in the presence of $[Rh(OH)((R)\text{-binap})]_2$[10] (5 mol% of Rh) in toluene at 80 °C for 12 h gave **3am** in 71% yield with 30% ee (entry 1). The ratio of allene **1a** to phenol **2m** had a significant influence on the enantioselectivity (entries 1–3); thus, the use of excess allene **1a** (2 equiv.) gave 55% ee of **3am** (entry 3). Other axially chiral biarylbisphosphines related to binap were also examined, where the reaction was catalyzed with 5 mol% rhodium catalyst generated *in situ* by mixing $[Rh(OH)(cod)]_2$[11] with the ligands. The use of (*R*)-segphos[12] gave **3am** in 32% yield with 64% ee (entry 4). Sterically bulky bisphosphine ligand (*R*)-DTBM-segphos[12]



Scheme 1 Asymmetric hydroarylation and hydroalkynylation catalyzed by rhodium complexes.

Table 1 The asymmetric addition of *p*-methoxyphenol (**2m**) to diphenylphosphinylallene **1a**[a]



Entry	**1**/mmol, **2**/mmol	Ligand	Solvent	NMR yield (%)[b]	ee (%)[c]
1[d]	0.2, 0.2	(*R*)-binap	Toluene	71	30
2[d]	0.2, 0.4	(*R*)-binap	Toluene	85	23
3[d]	0.4, 0.2	(*R*)-binap	Toluene	72	55
4	0.4, 0.2	(*R*)-segphos	Toluene	32	64
5	0.4, 0.2	(*R*)-DTBM-segphos	Toluene	69	80
6	0.4, 0.2	(*R*)-DTBM-segphos	*t*-BuOH	99	82

[a] Reaction conditions: $[Rh(OH)(cod)]_2$ (5 mol% of Rh), ligand (6 mol%), solvent (0.4 mL), 80 °C, 12 h. [b] Determined with CH_3NO_2 as an internal standard. [c] Determined by HPLC analysis with a chiral stationary phase column: Chiralcel OJ–H. [d] $[Rh(OH)((R)\text{-binap})]_2$ (5 mol% of Rh) was used.

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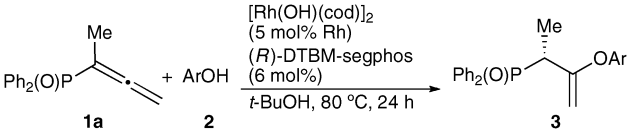
† Electronic supplementary information (ESI) available: Experimental procedures and compound characterization data. CCDC 713591. For ESI and crystallographic data in CIF or other electronic format, see DOI: 10.1039/b900976k

‡ This article is part of a ChemComm 'Catalysis in Organic Synthesis' web-theme issue showcasing high quality research in organic chemistry. Please see our website (http://www.rsc.org/chemcomm/organicwebtheme2009) to access the other papers in this issue

Table 2 Asymmetric hydroalkoxylation of allene **1a**[a]



Entry	2	Ar	3	Yield (%)[b]	ee (%)[c]
1	**2m**	4-$MeOC_6H_4$	**3am**	96	84
2	**2n**	3,4-$(OCH_2O)C_6H_3$	**3an**	93	80
3	**2o**	4-MeC_6H_4	**3ao**	96	80
4[d]	**2p**	2-MeC_6H_4	**3ap**	91	87
5[d]	**2q**	5-(*i*-Pr)-2-MeC_6H_3	**3aq**	86	85
6	**2r**	C_6H_5	**3ar**	99	85
7	**2s**	4-FC_6H_4	**3as**	99	84
8	**2t**	4-ClC_6H_4	**3at**	92	93(*R*)[e]
9	**2u**	3-ClC_6H_4	**3au**	99	94
10	**2v**	2-naphthyl	**3av**	99	91
11	**2w**	1-naphthyl	**3aw**	99	97

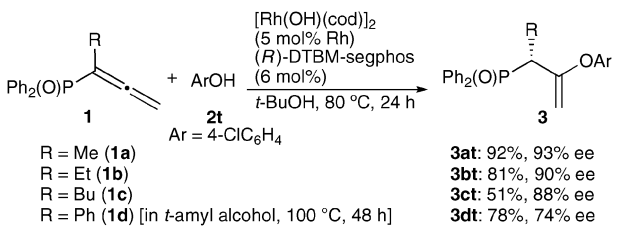
[a] Reaction conditions: **1a** (0.4 mmol), **2** (0.2 mmol), $[Rh(OH)(cod)]_2$ (5 mol% of Rh), (*R*)-DTBM-segphos (6 mol%), *t*-BuOH (0.4 mL), 80 °C, 24 h. [b] Isolated yields. [c] Determined by chiral HPLC analysis. [d] For 48 h. [e] Determined by X-ray analysis.

displayed a high enantioselectivity (80% ee), although the yield was modest (69% yield; entry 5). The reaction in *tert*-butyl alcohol as a solvent gave a quantitative yield of **3am** with 82% ee (entry 6).

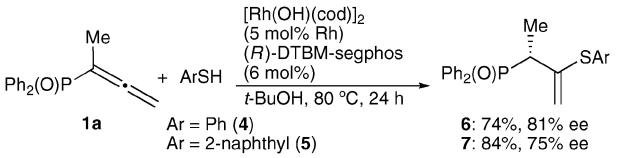
Table 2 summarizes the results obtained for the reactions of phenols **2** with diphenylphosphinylallene **1a**, which were carried out in the presence of rhodium/(*R*)-DTBM-segphos as a catalyst (5 mol% of Rh). Phenols **2m–2u** bearing either electron-donating or -withdrawing groups were introduced onto allene **1a** with high enantioselectivities, to give the corresponding vinyl ethers, **3am–3au**, in 80–94% ee (entries 1–9). The *ortho*-substituent (*o*-Me; entries 4 and 5) and the electron-withdrawing group (Cl; entries 8 and 9) on the benzene ring increased the enantioselectivity. High enantioselectivities were also observed for the addition of naphthols **2v** and **2w**, giving the corresponding vinyl ethers, **3av** and **3aw**, in 91 and 97% ee, respectively (entries 10 and 11). The absolute configuration of **3at** was determined to be *R* by X-ray crystallography (ESI†).

The hydroalkoxylation of allenes substituted with Et (**1b**), Bu (**1c**) and Ph (**1d**) groups also took place to give the corresponding vinyl ethers, the enantioselectivity being lower with more bulky substituents (Scheme 2).

This catalytic system was successfully applied to the hydrosulfenylation of allene **1a** (Scheme 3).[13] Thus, the addition of benzenethiol (**4**) and naphthalene-2-thiol (**5**) gave the



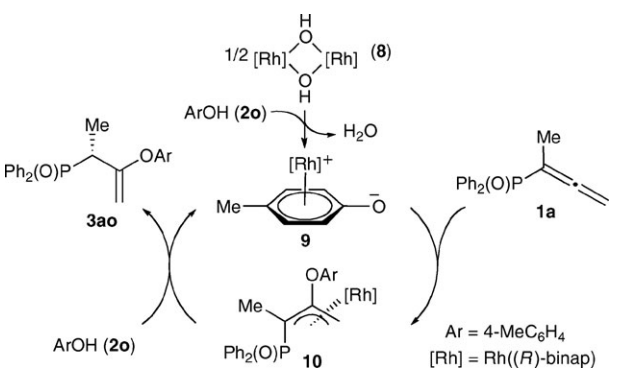
Scheme 2 The asymmetric addition of **2t** to diphenylphosphinylallenes **1**.



Scheme 3 The asymmetric hydrosulfenylation of allene **1a**.

corresponding vinyl thioethers, **6** and **7**, in 81 and 75% ee, respectively.

NMR studies on the catalytic reaction using hydroxorhodium complex $[Rh(OH)((R)\text{-binap})]_2$ (**8**) provided us with significant information on the catalytic cycle (Scheme 4). Treatment of **8** with *p*-cresol (**2o**) (10 equiv. to Rh) in C_6D_6 at 30 °C for 1 h brought about the selective formation of a new rhodium complex. The ^{31}P NMR spectrum of the reaction mixture showed a doublet peak at 45.2 ppm (J_{Rh-P} = 207 Hz), which was assigned to be π-phenoxorhodium complex **9** by the similarity of its ^{31}P NMR spectrum to that of $[Rh(PPh_3)_2(\pi\text{-}C_6H_5O)]\cdot 2(C_6H_5OH)$.[14] The ^1H NMR spectrum of **9**, which showed four non-equivalent aromatic protons (3.40 (dd, J = 7.3, 1.9 Hz, 1H), 4.02 (dd, J = 6.8, 2.1 Hz, 1H), 5.56 (dd, J = 6.8, 1.4 Hz, 1H), 6.34 (dd, J = 7.3, 1.9 Hz, 1H) ppm) on the coordinated benzene ring, also supported the structure of complex **9**. To the solution of rhodium complex **9** (Fig. 1b) generated from $[Rh(OH)((R)\text{-binap})]_2$ (**8**) (Fig. 1a) and 10 equiv. of phenol **2o**, was added 5 equiv. of allene **1a** (Fig. 1c), and the reaction was monitored by ^{31}P NMR. Within 1.5 h, the formation of a new rhodium complex was observed (Fig. 1d), which was assigned to be π-allylrhodium complex **10**[15] by ^{31}P NMR, which consisted of a doublet at 35.7 (J_{P-P} = 14 Hz), a ddd at 39.8 (J_{Rh-P} = 193 Hz, J_{P-P} = 39, 14 Hz) and a dd at 43.5 (J_{Rh-P} = 193 Hz, J_{P-P} = 39 Hz) ppm.[7,8] During the catalytic reaction of **1a** and **2o** to give **3ao**, both rhodium complexes **9** and **10** were observed, with the ratio of **9** to **10** being changed depending on the conversion (Fig. 1d–g). Allene **1a** was completely converted to **3ao** after 80 h at 30 °C, where complexes **8** and **9** were the observable rhodium complexes (Fig. 1h). These results support the catalytic cycle shown in Scheme 4,[16] where protonolysis[8,17] of the π-allylrhodium with phenol **2o** gives hydroalkoxylation product **3ao**, regenerating phenoxorhodium **9**. The observation of both key intermediates **9** and **10** at the same time throughout the catalytic reaction indicates a comparable reaction rate for the two key steps, π-allylrhodium formation and its protonation, in the catalytic cycle. Provided that π-allyl



Scheme 4 Observation of the intermediates in the catalytic cycle.

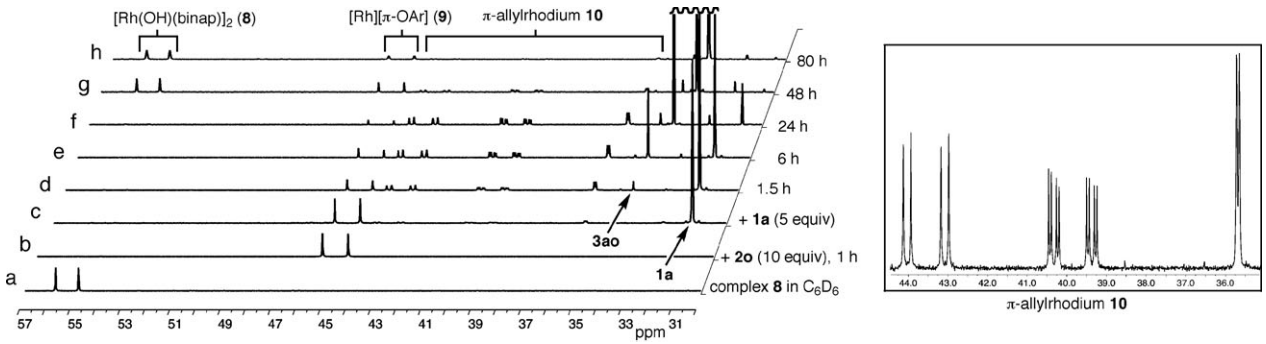


Fig. 1 Time course of the reaction monitored by ^{31}P NMR in C_6D_6 at 30 °C.

intermediate **10** has a similar structure to that decided for the hydroarylation of **1a**,[7] the absolute configuration *R* of the addition product **3at** implies that the π-allyl undergoes protonation from the side opposite to rhodium.

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