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Palladium-Catalyzed Asymmetric Ring Expansion of Allenylcyclobutanols: An Asymmetric Wagner−Meerwein Shift

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To improve the efficiency of the synthesis of bioactive natural products, it is essential to develop new reactions in which bond formation has high atom economy, as well as chemo-, regio-, diastereo-, and enantioselectivity.[1] In this regard, transition-metal-catalyzed asymmetric allylic alkylation (AAA) is one of the most powerful tools.[2,3] It has been shown that our family of ligands (Figure 1) can perform various palladium-catalyzed AAA reactions with excellent selectivity.[4]

Nevertheless, to generate the π-allylpalladium intermediate in allylic alkylation reactions, ionization of the leaving group is normally required. To enhance the simplicity and efficiency, a new method is required to initiate the reaction. Considering the hydrocarbonation of allenes catalyzed by palladium,[5,6] our group has recently utilized the hydropalladation mechanism to generate the π-allylpalladium intermediate and achieve catalytic asymmetric addition of pronucleophiles to allenes,[7] which fulfills the twin goals of high selectivity and atom economy.

We wondered whether the hydropalladation strategy could extend to intramolecular reactions, such that a catalytic asymmetric Wagner−Meerwein shift might be possible.[8] Although a recent report showed that carbopalladation of allenyl−cyclobutanols could generate a π-allylpalladium intermediate that undergoes a Wagner−Meerwein shift, these reactions were not enantioselective.[9] In this paper, we describe our efforts to effect asymmetric hydropalladation using palladium catalysts bearing our ligands that enable the catalytic asymmetric Wagner−Meerwein shift with allenylcyclobutanols initiated by hydropalladation (Scheme 1).

We chose benzyloxyallenylcyclobutanol **1** to begin the study. Without any additives, the ring expansion was very sluggish and gave low conversion. Both acidic conditions and higher temperatures accelerated the process. Interestingly, the combination of acid and base, for example benzoic acid and triethylamine, gave the fastest reaction, which is consistent with our earlier results on the intermolecular nucleophilic addition of benzyloxyallene,[7] in which the control of pH is the key to good reactivity and selectivity.

With benzoic acid and triethylamine as the additives, the reaction was carried out with good yields and enantioselectivity at 60 °C (Table 1). We further optimized the reaction conditions by varying ligand, solvent, additive, and temperature. The ee varied in different solvents (Table 1, entries 1−7). For **L1**, dichloro-ethane gave the best ee at 60 °C (Table 1, entry 7). Among our four ligands, **L3** gave the higher ee for the ring expansion of benzoxyallenylcyclobutanol (Table 1, entries 7−10). Moreover, **L3** gave the highest reactivity in this ring-expansion reaction. This result allowed us to lower the temperature to 30 °C or r.t. (Table 1, entries 10−13), which resulted in a higher ee but a slight drop in yield. The decline in yield was caused by the hydrolysis of the alkoxyallene competing with ring-expansion reactions at the lower temperatures. By adding 4 Å MS to prevent hydrolysis, we were able to improve the yield to 96% (Table 1, entry 14).

With the optimized reaction conditions, we examined the scope of the reaction by using different substrates (Table 2). The reaction

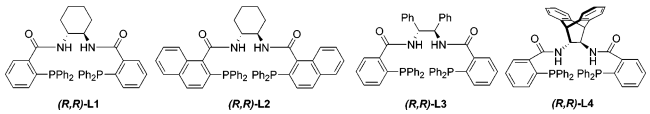


Figure 1. Trost ligands.

Scheme 1. Rationale for Palladium-Catalyzed Ring Expansion

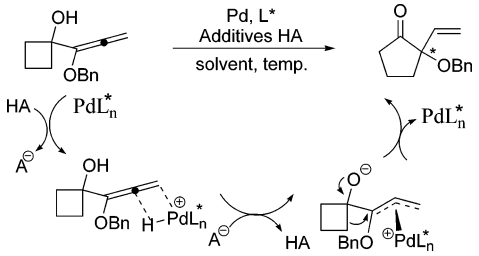
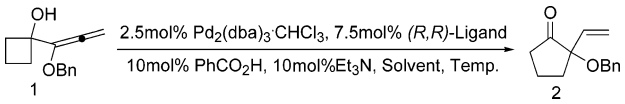


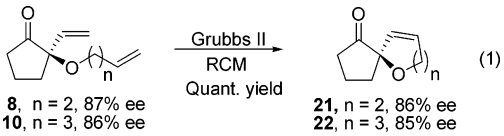
Table 1. Optimization of Ring-Expansion Reactions[a]



entry	ligand	solvent	*T* (°C)	yield (%)[b]	ee (%)[c]
1	**L1**	DMSO	60	41	64
2	**L1**	DMF	60	85	79
3	**L1**	CH_3CN	60	63	82
4	**L1**	Dioxane	60	40	80
5	**L1**	THF	60	90	80
6	**L1**	DME	60	89	81
7	**L1**	DCE	60	85	83
8	**L2**	DCE	60	33	57
9	**L3**	DCE	60	95	87
10	**L4**	DCE	60	86	84
11	**L3**	DCE	40	90	88
12	**L3**	DCE	30	75	92
13	**L3**	DCE	23	60	94
14[d]	**L3**	**DCE**	**30**	**96**	**92**

[a] Unless otherwise indicated, all reactions were performed using on a 0.2 mmol scale at 0.1 M for 2−24 h. [b] Isolated yield. [c] The ee values were determined by chiral HPLC. [d] Adding 4 Å MS.

tolerates a range of groups, including benzyl (Table 2, entry 1), 4-methoxybenzyl (Table 2, entry 2), simple alkyl (Table 2, entry 3), alkene (Table 2, entries 4 and 5), alkyne (Table 2, entry 6), and ester (Table 2, entry 10). It potentially provides various approaches to further functionalize, and thereby access, different synthetic targets. For instance, **8** and **10** can be used to synthesize chiral [4, 5] and [4, 6] spiro-ring systems, **21** and **22**, very simply by ring-closing metathesis (eq 1).

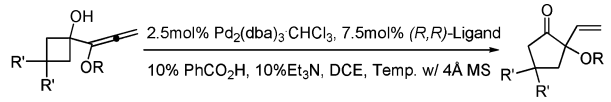


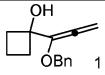
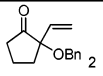
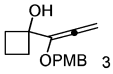
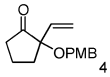
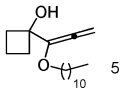
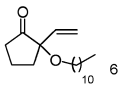
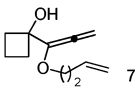
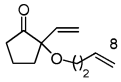
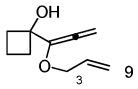
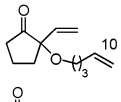
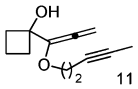
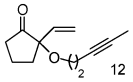
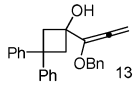
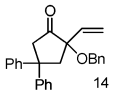
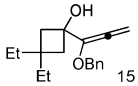
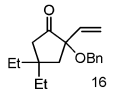
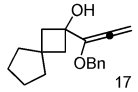
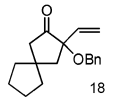
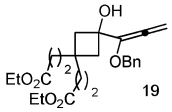
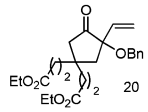
8, n = 2, 87% ee
10, n = 3, 86% ee

21, n = 2, 86% ee
22, n = 3, 85% ee (1)

10.1021/ja0602501 CCC: $33.50

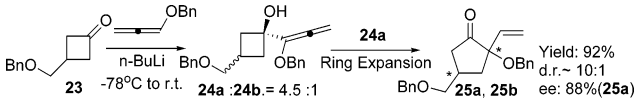
Table 2. Wagner−Meerwein Shift of Various Allenylcyclobutanols[a]



Entry	substrate	product	yield[d]	ee[e]
1	 1	 2	96%	92%
2[b]	 3	 4	97%	89%
3[b]	 5	 6	100%	86%[f]
4[b]	 7	 8	78%	87%[f]
5[b]	 9	 10	100%	86%[f]
6[b]	 11	 12	88%	84%[f]
7[c]	 13	 14	95%	95%
8[c]	 15	 16	92%	94%
9[c]	 17	 18	93%	92%
10[c]	 19	 20	80%	94%

[a] Unless otherwise indicated, all reactions were performed on 0.5 mmol scale at 0.1 M for 12 h at 23 °C using **L3**. [b] Performed at 30 °C using **L3**. [b] Performed at 60 °C using **L4**. [d] Isolated yield. [e] Unless otherwise indicated, ee values were determined by chiral HPLC. [f] ee values were determined by chiral GC.

Scheme 2. Diastereoselectivity of 3-Monosubstituted Cyclobutanol

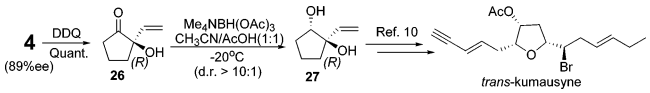


We have also studied 3,3-disubstituted cyclobutanols. However, their reactivity was poorer than the unsubstituted cyclobutanols and gave lower conversion at 30 °C. Reaction at elevated temperature (60 °C) gave a full conversion with 10−20% decrease in ee using **L3**. Switching to ligand **L4**, which gives a higher ee at 60 °C, solves this problem. This improvement is mainly due to **L4**'s rigid backbone, which makes its enantioselectivity more independent of the reaction temperature. As a result, we can perform the ring expansion of 3,3-disubstituted cyclobutanols at 60 °C maintaining good ee (Table 2, entries 7−10).

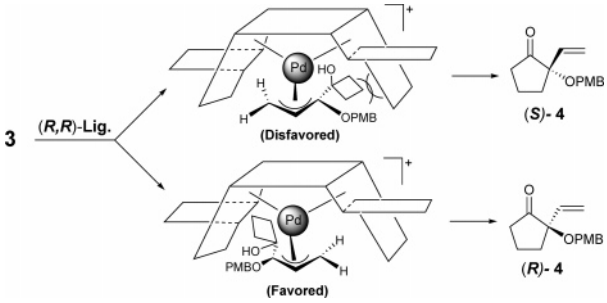
This methodology is also amendable for 3-monosubstitued substrates, for example **24** (Scheme 2). Subjecting the major addition product **24a** to the ring expansion allows us to selectively generate two stereogenic centers of cyclopentanone **25** in one step.

The assignment of the absolute configuration was made by conversion to the diol **27** (Scheme 3), a known compound whose asymmetric synthesis depended upon a chiral auxiliary.[10] This

Scheme 3. Assignment of the Absolute Configuration



Scheme 4. Mechanistic Rationale



compound served as a useful intermediate to synthesize highly functionalized tetrahydrofuran natural products, for example *trans*-kumausyne.[10] The stereochemistry of compound **4** could be rationalized by our proposed working model (Scheme 4).

In summary, we have developed a useful new method for the catalytic atom economic asymmetric Wagner−Meerwein shift of allenylcyclobutanols catalyzed by palladium, which provides a general way to synthesize cyclopentanones with α-chiral *O*-tertiary center. Moreover, the use of 3-monosubstituted substrate enables us to obtain excellent diastereoselectivity and enantioselectivity. Studies of the mechanism and other substrates are underway.

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Supporting Information Available: Experimental procedures and characterization data for all new compounds (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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