Cycloadditions

Phosphane-Free Rhodium Catalyst in an Anionic Micellar System for [4+2] Annulation of Dienynes**

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Cationic complexes often exhibit marked catalytic activity in a number of transition-metal-catalyzed reactions because they have more available vacant sites for coordination of substrates than the corresponding neutral complexes. In particular, cationic rhodium catalysts are frequently employed as homogeneous catalysts for hydrogenation, asymmetric hydrogenation, hydrosilylation, hydride transfer, cycloaddition, and so forth.[1] Cationic rhodium catalysts are usually prepared by treatment of the corresponding chloro complex with silver salts with outer-sphere counteranions, such as BF_4^- or PF_6^-.[2] Herein we report a phosphane-free cationic rhodium species that forms a highly active catalyst in an aqueous anionic micellar system for the [4+2] annulation of dienynes.[3]

We investigated the rhodium-catalyzed intramolecular [4+2] annulation of 1,3-dien-8-ynes **1a** in aqueous media (Table 1).[4,5] This process often employs cationic rhodium complexes as the catalyst. The presence of phosphane ligands is also crucial, and it was reported that 1,4-diphenylphosphanylbutane provides a highly efficient catalyst.[5g]

A water-soluble rhodium catalyst was prepared in situ from $[\{RhCl(cod)\}_2]$ and the trisodium salt of tris(*m*-sulfonatophenyl)phosphane (tppts).[6,7] The addition of dienyne **1a** to a solution of the catalyst at 50 °C provided the cycloaddition product **2a** in 51 % yield after stirring for 12 h (Table 1, entry 1). The aromatized product **3a** was also obtained. The reaction system was heterogeneous, and the addition of surfactants was examined.[8] An anionic surfactant, sodium dodecyl sulfate (SDS), enhanced the efficiency of the reaction, and the yield of **2a** was improved to 91 % (Table 1, entry 4). Cationic and neutral surfactants did not work as effectively as SDS (Table 1, entries 2 and 3).

We then tried to lower the reaction temperature to room temperature (Table 1, entries 5–12). None of the cycloaddition product was observed at 25 °C with the catalyst combination of $[\{RhCl(cod)\}_2]$–tppts (Table 1, entry 5). The use of diphenylphosphanylbutane (dppb) yielded a small amount of **2a** (Table 1, entry 6). After several experiments, we found that the rhodium chloride dimer without any phosphane ligands led to quantitative conversion (Table 1, entry 7). Mixing the rhodium chloride dimer and SDS in water afforded a clear yellow homogeneous solution, although $[\{RhCl(cod)\}_2]$ itself is insoluble in water. Several rhodium complexes were tested in 20-min reactions (Table 1, entries 8–12). The Wilkinson complex and $[\{RhOH(cod)\}_2]$ did not exhibit catalytic activity (Table 1, entries 9 and 10, respectively). The norbornadiene (nbd) complex proved to be a more efficient catalyst precursor than the corresponding cyclooctadiene complex (Table 1, entry 11). Almost quantitative conversion within 20 min at room temperature was observed. In contrast, the ethylene complex did not work at all (Table 1, entry 12). On the basis of the difference between these rhodium complexes we speculate that the alkene ligand is still associated with the rhodium atom in water.

With an efficient reaction protocol in hand for the rhodium-catalyzed [4+2] annulation in water, the reaction with several dienynes **1** was examined. Table 2 summarizes the results. Hydrophilic dienyne **1b** was very reactive and was converted quantitatively within 10 min. Notably, the reaction can be conducted under an air atmosphere (Table 2, entry 5). Nitrogen-tethered dienyne **1e** also afforded the annulation product in excellent yield (Table 2, entry 6). It seems that

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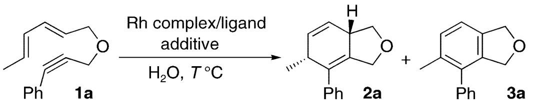
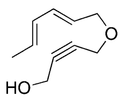
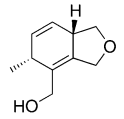
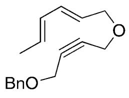
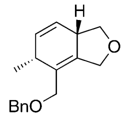
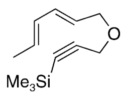
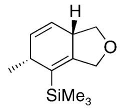
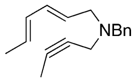
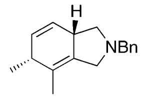
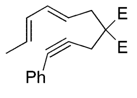
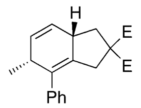
Table 1: Optimization of reaction conditions.



Entry	Catalyst (mol %)	Ligand (mol %)	Additive (equiv)	T [°C]	t [min]	Yield [%]	
						2a	**3a**
1	$[\{RhCl(cod)\}_2]$ (2.5)	tppts (20)	none	50	720 (12 h)	51	14
2	$[\{RhCl(cod)\}_2]$ (2.5)	tppts (20)	Oct_3NMeCl (2.0)	50	120	32	–
3	$[\{RhCl(cod)\}_2]$ (2.5)	tppts (20)	TritonX-100 (2.0)	50	120	27	–
4	$[\{RhCl(cod)\}_2]$ (2.5)	tppts (20)	SDS (2.0)	50	120	91	–
5	$[\{RhCl(cod)\}_2]$ (2.5)	tppts (20)	SDS (2.0)	25	120	–	–
6	$[\{RhCl(cod)\}_2]$ (2.5)	dppb (5)	SDS (2.0)	25	60	6	–
7	$[\{RhCl(cod)\}_2]$ (2.5)	none	SDS (2.0)	25	60	96	–
8	$[\{RhCl(cod)\}_2]$ (1.25)	none	SDS (2.0)	25	20	26	–
9	$[RhCl(PPh_3)_3]$ (1.25)	none	SDS (2.0)	25	20	–	–
10	$[\{RhOH(cod)\}_2]$ (1.25)	none	SDS (2.0)	25	20	–	–
11	$[\{RhCl(nbd)\}_2]$ (1.25)	none	SDS (2.0)	25	20	93	–
12	$[\{RhCl(CH_2{=}CH_2)_2\}_2]$ (1.25)	none	SDS (2.0)	25	20	–	–
13	$[\{RhCl(nbd)\}_2$ (1.25)]	none	$MeOSO_3Na$ (2.0)	25	20	–	–
14	$[\{RhCl(nbd)\}_2$ (1.25)]	none	SDS (0.025)	25	20	43	–

Table 2: Rhodium-catalyzed intramolecular [4+2] annulation in water.[a]

Entry	Dienyne	t [min]	Product	Yield [%]
1	**1a**	25	**2a**	93
2	 **1b**	10	 **2b**	97
3	 **1c**	60	 **2c**	99
4	 **1d**	120	 **2d**	95
5[b]	**1d**	120	**2d**	92
6	 **1e**	30	 **2e**	96
7[c]	 **1f**	(24 h)	 **2f**	71

[a] Reaction conditions: $[\{RhCl(nbd)\}_2]$ (0.0031 mmol), sodium dodecyl sulfate (0.5 mmol), H_2O (2.5 mL), **1** (0.25 mmol), room temperature. [b] The reaction was carried out under air. [c] E = CO_2Et.

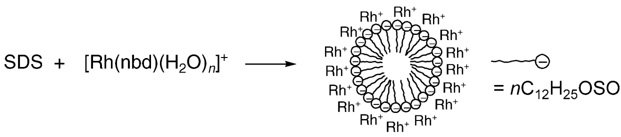
increased hydrophobicity of the substrate retards the reaction. The reaction with highly hydrophobic substrate **1f** was sluggish and took 24 h to provide the product in satisfactory yield (Table 2, entry 7).

We propose that rhodium chloride dissociates to provide a reactive cationic rhodium species in highly polarized reaction media (Scheme 1). In fact, a significant amount of chloride anion was detected in the catalyst solution by ion-electrode analysis. The concentration of Cl^- in the catalyst solution of $[\{RhCl(nbd)\}_2]$–SDS was measured to be $2.54\times10^{-3}\,mol\,L^{-1}$ by ion-electrode analysis, whereas it was calculated to be $2.50\times10^{-3}\,mol\,L^{-1}$, provided that the Rh–Cl bond is completely dissociated. This result strongly suggests the formation of cationic rhodium in the presence of SDS. On the other hand, $[Cl^-]$ was $1.29\times10^{-3}\,mol\,L^{-1}$ in an aqueous solution of $[\{RhCl(nbd)\}_2]$–Triton X100. An anionic surfactant is essential for the efficient formation of cationic rhodium species.

$$[\{RhCl(nbd)\}_2] + H_2O \xrightarrow{SDS} [Rh(nbd)(H_2O)_n]^+ + [Cl(H_2O)_m]^-$$

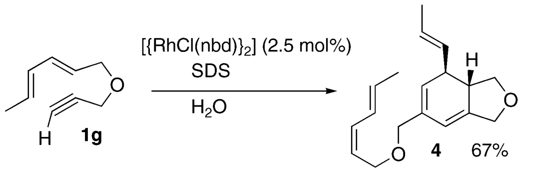
Scheme 1. Dissociation of the Rh–Cl bond in water.

In water, SDS forms micelles, which are negatively charged owing to the sulfate groups. The anionic charge of the micelles would concentrate the cationic rhodium species, which induces rapid conversion of dienyne **1** (Scheme 2). The fact that cationic and neutral surfactants did not work highlights the importance of the charge interaction between the anionic micelle and the cationic rhodium species. Furthermore, sodium methyl sulfate instead of SDS yielded none of the desired products (Table 1, entry 13). It is known that sodium methyl sulfate does not form micelles.[9] Furthermore, the reaction was significantly slow below the critical micelle concentration of SDS (Table 1, entry 14). Micelle formation is crucial for this reaction system. Furthermore, both $[\{RhCl(nbd)\}_2]$ and the $[\{RhCl(nbd)\}_2]$–SDS combination did not exhibit catalytic activity at all in organic solvents such as dichloromethane or benzene.



Scheme 2. Presumed formation of micellar catalyst.

To our surprise, the reaction of **1g** provided the *intermolecular* annulation product **4**, the dimer of **1g**, in 67 % yield as a single stereoisomer in an aqueous reaction system (Scheme 3).[10] In organic solvents, the reaction of **1g** usually provides *intramolecular* annulation products under rhodium catalysis. Very recently, Gilbertson and DeBoef reported



Scheme 3. Rhodium-catalyzed intermolecular [2+2+2] annulation.

intermolecular [4+2+2] annulation of **1g** with terminal alkynes.[11] It is intriguing that **1g** undergoes three distinct modes of annulation reactions under rhodium catalysis: intramolecular [4+2], intermolecular [4+2+2], and intermolecular [2+2+2] annulations, depending on the fine-tuned reaction conditions.

In conclusion, the combination of $[\{RhCl(nbd)\}_2]$–SDS in water provides cationic rhodium species that act as a highly active catalyst system for intramolecular [4+2] annulation of 1,3-dien-8-ynes. Further research on the exact nature of the catalyst combination is currently underway in our laboratory.

Experimental Section

In a 20-mL flask, $[\{RhCl(nbd)\}_2]$ (1.5 mg, 0.00313 mmol) and sodium dodecyl sulfate (144 mg, 0.5 mmol) were placed under an argon atmosphere. Pure water (2.5 mL) was introduced, and the mixture was stirred at room temperature for 10 min. A clear, yellow solution was obtained. Hexa-2,4-dienyl 3-phenylprop-2-ynyl ether (**1a**, 52.3 mg, 0.246 mmol) was added to the mixture through a microsyringe. The mixture was stirred vigorously for 20 min and then extracted with ethyl acetate. The organic extracts were dried through a short pad of silica gel on a Na_2SO_3 layer. Concentration followed by purification of the residual oil afforded 6-methyl-7-phenyl-1,3,3a,6-tetrahydroisobenzofuran (**2a**, 48.6 mg, 0.23 mmol) in 93 % yield.

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