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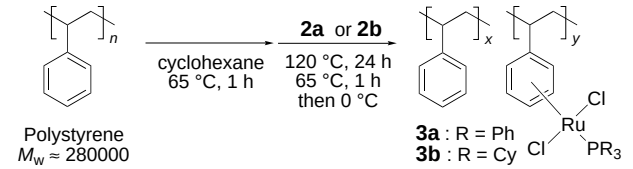
A Novel Polymer-Supported Arene – Ruthenium Complex for Ring-Closing Olefin Metathesis**

Ryo Akiyama and Shū Kobayashi*

Arene – ruthenium complexes are very useful precatalysts for several organic reactions, such as transfer hydrogenation,[1] Diels – Alder reaction,[2] olefin cyclopropanation,[3] enol formate formation,[4] cyclization of dienylalkyne,[5] and olefin metathesis.[6] While the catalysts prepared from the arene – ruthenium complexes are air- and moisture-sensitive, expensive, and cannot be recovered in many cases, immobilized catalysts are expected to solve these problems. Although several polymer-supported ruthenium complexes have been reported,[7] however, these are not without problems, such as tedious procedures for the preparation of the complexes, low activity compared with the original catalysts, and difficulty of applying the catalysts to other reactions. Therefore, development of more versatile polymer-supported ruthenium complexes is strongly demanded. Herein, we describe a novel polymer-supported arene – ruthenium complex that is recovered quantitatively and reused for ring-closing olefin metathesis and other reactions.

Our idea is to utilize the benzene rings of polystyrene as ligands to immobilize arene – metal complexes. However, it is known that arene-displacement reactions at Ru^{II} centers are often sluggish.[8] Thus, we carefully chose [{Ru(η^6-$C_6H_5CO_2Et$)Cl_2}$_2$] (**1**) as the starting material, because it was reported that an intramolecular arene exchange proceeded in good yield using **1** instead of [{Ru(η^6-*p*-cymene)Cl_2}$_2$].[9] Dimer **1** was easily prepared according to the literature procedure,[8, 9] and treatment of **1** with triphenylphosphane or tricyclohexylphosphane gave [Ru(η^6-$C_6H_5CO_2Et$)(PR_3)Cl_2] (**2a**: R = Ph, **2b**: R = Cy) quantitatively.

Preparation of the polymer-supported arene – ruthenium complexes using **2** was successfully performed based on a procedure which is similar in part to that of formation of microcapsules (Scheme 1).[10, 11] All other methods we tested



Scheme 1. Synthesis of polymer-supported [(arene)$RuCl_2(PR_3)$] (**3**).

did not give satisfactory results. The structure of the polymer-supported arene – ruthenium complexes was confirmed by NMR spectroscopic analysis. We measured the ^{31}P swollen-resin magic-angle spinning (SR-MAS) NMR spectra[12] of the catalysts, and only one peak arising from PR_3 (**3a** R = Ph: δ = 25.7 ppm, **3b** R = Cy: δ = 28.5 ppm) coordinating to the ruthenium was observed.[13] From these results, we concluded that the catalyst was supported as [(arene)$RuCl_2(PR_3)$] (polymer-supported [(arene)$RuCl_2(PR_3)$] (**3;** PS-$RuCl_2(PR_3)$)). To our knowledge, this is the first example of a polymer-supported ruthenium catalyst, in which the benzene rings of the polymer coordinated to the ruthenium to immobilize the catalyst onto the polymer.

PS-$RuCl_2(PR_3)$ was used in the ring-closing olefin metathesis (RCM). We prepared a polymer-supported cationic ruthenium – allenylidene complex according to the Dixneuf and Fürstner method.[6b,c] PS-$RuCl_2(PPh_3)$ (**3a**), tricyclohexylphosphane (PCy_3), 1,1-diphenyl-2-propynol (**4**), and sodium hexafluorophosphate ($NaPF_6$) were mixed in several solvents, and the mixture was stirred for 1 h under reflux. Signals of the

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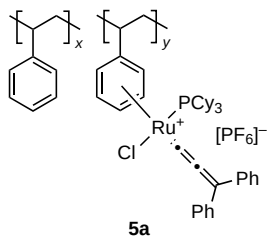


5a

^{31}P SR-MAS NMR spectra of the activated ruthenium catalyst (**5a**) thus prepared were observed at 50.8 and −144.0 ppm.[14] We then tested **5a** in the RCM of *N*,*N*-diallyl-*p*-toluensulfonamide (**6**) in hexane (Table 1). It was found that the choice of solvents was crucial. While the desired product was obtained in good yield in the first run in *i*PrOH:hexane (1:1), the activity of the catalyst decreased significantly in the second and third runs

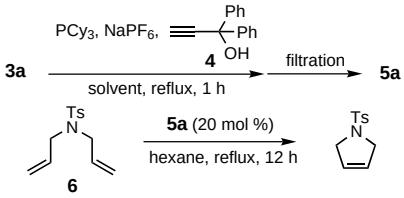


Table 1. Effect of solvents in the preparation of the active catalyst.

Entry	Solvent	Yield [%] (Recovery [%]) 1st	2nd	3rd
1	*i*PrOH	8 (quant)	9 (quant)	–
2	*i*PrOH:hexane (1:1)	78 (quant)	48 (quant)	16 (quant)
3	*i*PrOH:hexane (1:10)	42 (quant)	69 (quant)	71 (quant)
4	*i*PrOH:hexane (1:10)[a]	49 (98)	72 (quant)	77 (quant)

[a] **3b** was used instead of **3a**.

(entry 2). On the other hand, the yield of the desired product was very low in *i*PrOH (entry 1). In *i*PrOH:hexane (1:10), moderate yields were obtained. The activity of the catalyst was maintained even after the third use (entries 3 and 4).[15]

To increase the yields, we examined the reactivation conditions of the recovered catalysts in RCM reactions (Table 2). After careful investigation, the best results were obtained when a mixture of the recovered catalyst, PCy_3, and **4** was stirred for 1 h under reflux and, after addition of $NaPF_6$,

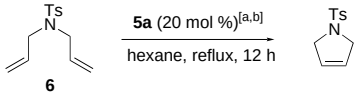


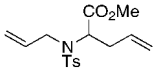
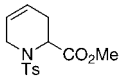
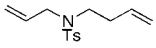
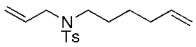
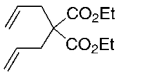
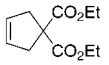
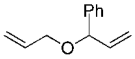
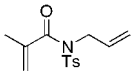
Table 2. Reactivation conditions of the catalyst.

Entry	Method (Conditions)		Yield [%] 1st	2nd	3rd
1	A	(PCy_3, **4**, reflux, 1 h)	40	72	77
2	B	(PCy_3, $NaPF_6$, **4**, RT, 12 h)	63	56	49
3	C	(PCy_3, **4** reflux, 1 h then $NaPF_6$, RT, 12 h)	69	73	85
4[c]	C		75	81	98[f]
5[c,d]	C		71	85	88
6[c,e]	C		97	18	12
7[c,g]			80		

[a] Catalyst **5a** was reactivated under method A–C in *i*PrOH:hexane (1:10). [b] Recovery of catalysts was quantitative. [c] Hexane:toluene (10:1) was used as a solvent in RCM. [d] 10 mol% of **5a** were used. [e] 5 mol% of **5a** were used. [f] 4th; 83% (recovery: quant), 5th; 82% (recovery: quant), 6th; 89% (recovery: quant), 7th; 92% (recovery: quant). [g] [(*p*-cymene)RuCl(PCy_3)(=C=C=CPh_2)]$^+$[PF_6]$^-$ was used instead of **5a**.

further stirred for 12 h at room temperature (method C). We tested several other examples of the PS–Ru-catalyzed RCM of olefins (Table 3).[11] Six-membered rings as well as five-membered rings were smoothly formed under these conditions, while sterically hindered diethyl diallylmalonate was less reactive (entry 4). Recovery of the catalyst was quanti-

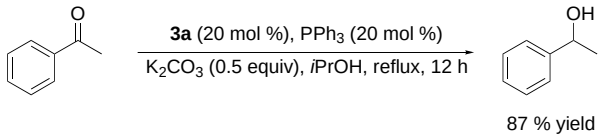
Table 3. Ring-closing olefin metathesis using **5a**.[a]

Entry	Substrate	Product	Yield [%]
1			98
2			92
3			57[b]
4			72
5			66
6			82

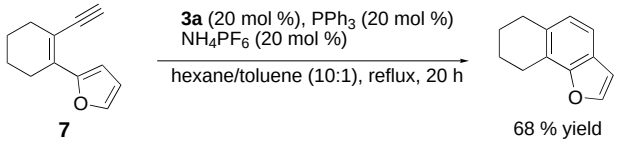
[a] All reactions were carried out using **5a** (20 mol%) in hexane:toluene (10:1) under reflux conditions for 12 h; Ts = tosyl [b] Reaction was carried out for 24 h.

tative in all cases, and the recovered catalyst could be reused without loss of activity. In addition, the structure of the recovered catalyst was confirmed by ^{31}P SR-MAS NMR spectroscopic analysis. Signals were observed at 50.8 and −144.0 ppm, which are consistent with those of the original catalyst **5a**.

Catalyst **3a** was successfully used in other reactions. Acetophenone was reduced smoothly in the presence of **3a** to afford the corresponding alcohol in high yield (Scheme 2). In addition, **3a** catalyzed the cyclization of the dienylalkyne **7** in good yield (Scheme 3).



Scheme 2. Hydrogenation of acetophenone using **3a**.



Scheme 3. Cyclization of dienylalkye using **3a**.

In summary, we have accomplished the first immobilization of arene–ruthenium complexes onto the benzene rings of polystyrene. The polymer-supported catalyst (PS-$RuCl_2$-

(PPh_3)) has been successfully used in RCM and other ruthenium(II)-catalyzed reactions. In all cases, the reactions proceeded in high yields, and the catalyst was recovered quantitatively by simple filtration and reused. Further investigation to apply P,S-$RuCl_2(PPh_3)$ to other ruthenium(II)-catalyzed reactions is now in progress.

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[11] Experimental details are shown in Supporting Information.

[12] The usefulness of the SR-MAS NMR technique for structure determination of resins directly, without cleavage from polymer supports has been demonstrated through the development of several useful reactions using the cross-linked polystyrene-based resins in the solid-phase in our laboratories. a) S. Kobayashi, R. Akiyama, T. Furuta, M. Moriwaki, *Molecules Online* **1998**, *2*, 35; b) S. Kobayashi, R. Akiyama, H. Kitagawa, *J. Comb. Chem.* **2000**, *3*, 196, and references therein. See also ref. [10e] and [10f].

[13] We prepared [Ru(η^6-*p*-cymene)(PPh_3)Cl_2] and measured ^{31}P NMR spectrum of this complex ($\delta = 23.1$ ppm); [Ru(η^6-*p*-cymene)(PCy_3)Cl_2] $\delta = 26.0$ ppm.[6c]

[14] ^{31}P SR-MAS NMR ($CDCl_3$): 50.8 (PCy_3), -144.0 ppm (PF_6^-). Solid PPh_3 ($\delta = -8.4$ ppm) was used as an external standard. ^{31}P NMR of monomeric ruthenium complex was measured in ref. [6c]. ^{31}P NMR ($CDCl_3$): 58.8 (PCy_3), -140.8 ppm (PF_6^-). See also A. Fürstner, O. Guth, A. Düffels, G. Seidel, M. Liebl, B. Gabor, R. Mynott, *Chem. Eur. J.* **2001**, *7*, 4811.

[15] That no leaching of ruthenium metal occured was confirmed by fluorecence X-ray analysis.

(*E*)-4-Hydroxy-3-methylbut-2-enyl Diphosphate: An Intermediate in the Formation of Terpenoids in Plant Chromoplasts**

Wenyun Gao, Reik Loeser, Maja Raschke, Marco A. Dessoy, Michael Fulhorst, Henriette Alpermann, Ludger A. Wessjohann,* and Meinhart H. Zenk*

Nature's terpenoids, with over 35000 known members, constitute compounds that are either essential for life (namely, cholesterol, vitamins) or represent secondary products, such as chemical attractants, defense compounds, and antibiotics. Until recently, terpenoids were assumed to be formed exclusively by the mevalonate pathway.[1] It has now been shown that an alternative metabolic route exists in plastids of higher plants and in the majority of bacteria. This pathway leads from pyruvate (**1**) and D-glyceraldehyde-3-phosphate (**2**) via 1-deoxy-D-xylulose phosphate (**3**, DXP, Scheme 1) and the intermediates **4**–**7** to the key metabolites isopentenyl diphosphate (**9**, IPP) and dimethylallyl diphosphate (**10**, DMAPP), which are essential to all organisms.[2] The cyclic diphosphate **7** has been proven to be a precursor to **9** and **10** in the alternative pathway and thus to plastidic isoprenoids, mainly phytoene (**11**).[3] This reaction involves a threefold, possibly stepwise, dehydroxylation at carbon atoms C-2, C-3, and C-4 of **7**.

On comparative phytochemical grounds, we postulated that (*E*)-4-hydroxy-3-methylbut-2-enyl diphosphate (**8**, Schemes 1 and 2) is a likely intermediate in the deoxyxylulose phosphate pathway between **7** and **9**/**10**.[4] This hydroxylated hemiterpene is seen biogenetically in numerous plant-derived products, such as the plant hormone **13**, the glucoside of (*E*)-2-

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