Preparation of a Resin-Bound Arene−Ruthenium Complex and Assessment of Its Use in Enol Formate Synthesis and Olefin Cyclopropanation

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Introduction

Recent interest in the development of environmentally benign synthesis has evoked a renewed interest in developing polymer-bound metal catalysts and reagents for organic synthesis that maintain high activity and selectivity.[1] Advantages of attaching a catalyst to a polymer support include ease of separation from the product mixture at the end of a reaction and the fact that attaching a metal complex to a polymer can reduce the toxicity and air sensitivity of the species considerably. In addition, as the catalyst is easily removed from the reaction mixture, it can be reused in subsequent reactions. As transition metal complexes are often expensive, attaching the species to a polymer support also has economic implications.

In this paper, we report the preparation and synthetic versatility of the polymer-supported arene ruthenium complex **1**. This and other arene ruthenium complexes are used frequently in metal-mediated organic synthesis for reactions as diverse as transfer hydrogenation,[2] Diels−Alder chemistry,[3] olefin cyclopropanation,[4] and enol formate formation.[5] For the purposes of our studies, we have focused attention on enol formate synthesis and cyclopropanation as representative reactions for comparing the activity of **1** with its nonsupported analogue [Ru(*p*-cymene)Cl_2(PPh_3)] (**2**). Our attention has particularly been focused on leaching, if any, of the metal complex from the polymer support and also on the effect of catalyst recycling.

Results and Discussion

Preparation of Polymer-Supported Catalyst 1. The polymer support chosen for immobilization of the ruthenium arene complex was commercially available "polymer-supported triphenylphosphine" (polystyrene cross-linked with 2% divinylbenzene; 3 mmol P/g resin). The immobilized complex **1** was prepared by thermolysis of the dimer [Ru(*p*-cymene)Cl_2] with the functionalized resin in dichloromethane/toluene (1:2) (Figure 1). Subsequent filtration, washing, and drying of the polymer gave a deep red powder that was characterized as **1** on comparison of spectroscopic data with that of the previously reported complex **2**,[6] which is also deep red in color. The assignment was further confirmed by elemental analysis, this also allowing us to determine the catalyst loading at 2.5 mmol per gram of resin. By varying the molar ratio of phosphine functionalized polymer to ruthenium arene dimer the P/Ru ratio could be varied but not increased above the threshold of 6:5. The polymer bound complex formed is stable in air, no decomposition being noted over the period of 3 months at room temperature.

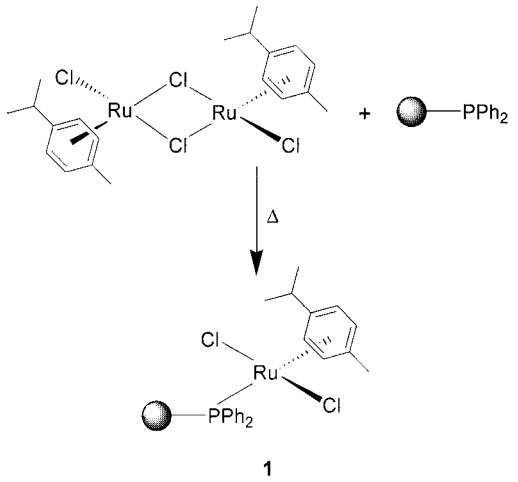

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Figure 1. Preparation of polymer-bound catalyst **1**.

Use of 1 as a Catalyst for Enol Formate Synthesis and Olefin Cyclopropanation. In the presence of a catalytic amount of **1**, the regioselective addition of formic acid to a range of terminal alkynes and diynes led to the formation of the corresponding enol formates in good yield as shown in Figure 2. For comparative purposes, reported yields for the analogous reactions using **2** are also shown.[5,7] From these results, it is clear that the attachment of the metal complex to the polymeric support has little effect on the yields of reaction compared to the homogeneous analogue. Reactions were performed in toluene as this led to optimum yields even though swelling of the beads is not as marked as in other solvents such as dichloromethane or thf.

In an attempt to show that **1** can be recycled, the reaction of phenylacetylene with formic acid was repeated five times using the same batch of supported catalyst. As seen in Table 1, the yields remain around 90%, clearly illustrating the reusability of the catalyst. The entire crude reaction mixture in each case was dissolved in $CDCl_3$ and analyzed by ^1H NMR spectroscopy. There

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(1) See, for example: (a) Zhang, T. Y.; Allen, M. J. *Tetrahedron Lett.* **1999**, *40*, 5813−5816. (b) Bayston, D. J.; Fraser, J. L.; Ashton, M. R.; Baxter, A. D.; Polywka, M. E. C.; Moses, E. *J. Org. Chem.* **1998**, *63*, 3137−3140. (c) Angelino, M. D.; Laibinis, P. E. *Macromolecules* **1998**, *31*, 7581−7587. (d) Hinzen, B.; Ley, S. V. *J. Chem. Soc., Perkin Trans. 1* **1998**, 1−2.

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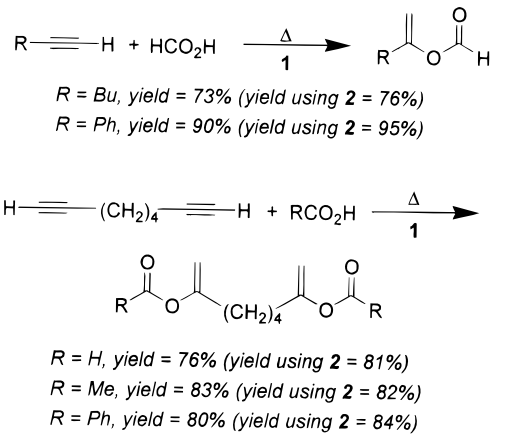

Figure 2. Use of **1** in enol formate synthesis.

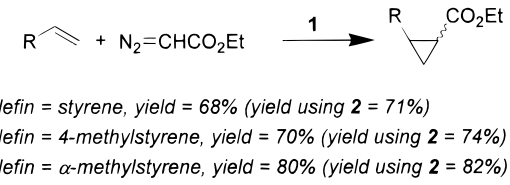

Figure 3. Use of **1** in olefin cyclopropanation.

Table 1. Reusability of 1

experiment	yield (%)
1	90
2	87
3	92
4	89
5	89

were no peaks characteristic for the presence of *p*-cymene coordinated ruthenium complexes observed, this suggesting that there was no observable catalyst leaching. This is a significant finding and is of key importance when considering the viability of using **1** in large-scale synthesis of fine chemicals where contamination of the product with heavy metals is highly undesirable.

Similar activity was found when using **1** in olefin cyclopropanation reactions. The cyclopropanation of a range of olefins using ethyl diazoacetate and a catalytic amount of **1** gave the desired products in comparable yield to when **2** is used,[8] as shown in Figure 3. Again, the catalyst can be reused a number of times and no leaching from the polymer support is observed.

In conclusion, we have shown that attachment of [Ru(*p*-cymene)Cl_2(PPh_3)] to polymer-supported triphenylphosphine leads to an air-stable, versatile immobilized catalyst that is as active as its homogeneous analogue and has the advantage that it can be reused numerous times. As such, this represents an example of a clean technology process, the only workup required consisting of a filtration to remove the polymer-supported catalyst then distillation to isolate the pure product. Work is currently underway to exploit the activity of other polymer-supported organometallic complexes in metal-mediated organic synthesis.

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Experimental Section

General Methods. All chemicals were reagent grade and used as purchased including polymer-supported triphenylphosphine (Fluka, 3 mmol P/g resin). All reactions were performed under an inert atmosphere of dry nitrogen using distilled dried solvents. The ^1H and $^{31}P\{^1H\}$ NMR spectra were recorded at 250 MHz and 293 K.

Preparation of Polymer-Supported Ruthenium Arene Complex 1. Commercially available polymer-supported triphenylphosphine was first washed several times with THF and then dichloromethane before being dried in vacuo and 100 mg added to a toluene solution of [Ru(*p*-cymene)Cl_2] (108 mg, 0.175 mmol). The resultant mixture was heated under reflux *without stirring* (to avoid breaking up the resin) for 2 h, during which time the originally light brown polystyrene beads turned deep red in color. After cooling, the beads were filtered off using a sintered funnel and washed five times with dichloromethane and then twice with hexane before drying in vacuuo. Loading of the ruthenium complex on the resin was found to be approximately 2.5 mmol/g resin by elemental analysis (comparison of P, Cl, and Ru content).

General Method for Enol Formate Synthesis Catalyzed by 1. Formic acid (1.10 mL, 20 mmol), alkyne (25 mmol), and **1** (80 mg, 1 mol % Ru complex) in toluene (20 mL) were refluxed for 15 h. After cooling, the polymer-bound catalyst was removed by filtration and the product distilled from the filtrate under reduced pressure (∼1 mmHg). Spectroscopic data for the products were compared with those in the literature,[5,7] showing formation of the appropriate enol formate. Yields of isolated products are shown in Figure 2.

Assessment of the Reuse of 1. The reaction of phenylacetylene with formic acid catalyzed by **1** was repeated five times using the same batch of polymer-bound catalyst. Between experiments, the catalyst was washed with dichloromethane and hexane and dried in vacuuo before placing it back in the reaction vessel. The crude product mixture was analyzed using ^1H and $^{31}P\{^1H\}$-NMR spectroscopy before the product was isolated and yield recorded for comparison (Table 1).

General Method for Olefin Cyclopropanation Catalyzed by 1. Ethyl diazoacetate (2.5 mL, 20 mmol in 5 mL CH_2Cl_2) was added in 0.25 mL portions over the period of 4 h to a dichloromethane solution of the olefin (25 mmol in 5 mL CH_2Cl_2) containing **1** (80 mg, 1 mol % Ru complex). The reaction mixture was held at 60 °C using a water bath and the solution agitated using a nitrogen bubble flow. At the end of the reaction, the catalyst was removed by filtration, solvent and excess olefin removed from the filtrate under reduced pressure, and the product mixture analyzed using ^1H NMR and GC techniques. Product yields were determined by GC through the use of experimentally measured response ratios. The NMR data collected were compared with those in the literature[8] confirming formation of the cyclopropane complexes. Yields are shown in Figure 3.

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