

Immobilized heterobimetallic Ru/Co nanoparticle-catalyzed Pauson–Khand-type reactions in the presence of pyridylmethyl formate

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Heterobimetallic Ru/Co nanoparticles, immobilized on charcoal, were synthesized and used as catalysts in the Pauson–Khand-type reaction in the presence of pyridylmethyl formate instead of carbon monoxide; the catalysts were effective for intra- and intermolecular reactions and easily reused without loss of catalytic activity.

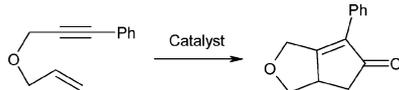
The development of new processes that are simultaneously economically sustainable and environmentally responsible represents one of challenges of the twenty-first century.¹ In this respect, catalysis plays a central role in the development of environmentally safe and clean chemical processes. The design and development of new catalysts as cleaner alternative synthetic pathways has attracted much attention. Transition metal-catalyzed cyclization reactions have established their importance in organic synthesis.² In particular, the cobalt-mediated carbonylative cocyclization of an alkyne and an alkene, known as the Pauson–Khand reaction, has become one of the most convergent and versatile methods for the construction of 5-membered rings.³ However, increasing environmental awareness has made the use of carbon monoxide undesirable and prompted the search for an alternative process that does not employ carbon monoxide or utilizes a substitute. *In situ* generated carbon monoxide could be a good candidate. However, the synthetic utilization of generated carbon monoxide has been largely ignored.⁴ Recently, the use of decarbonylated CO from formates or aldehydes has been utilized in transition metal-catalyzed hydroxycarbonylation,⁵ the Pauson–Khand reaction,⁶ and hydroesterification.⁷ Moreover, given the importance of not only the amount but also of the nature of waste products, the application of cleaner heterogeneous catalysts with readily available starting materials would allow the minimization of inorganic as well as organic waste production. Our own research interests have recently focused on the use of transition metal nanoparticles as heterogeneous catalysts in the Pauson–Khand reaction and related reactions.⁸ They are easily recovered and reused without the loss of catalytic activity in the intra- and intermolecular Pauson–Khand reaction. Recently, we have focused our efforts on the design and development of a new catalytic system consisting of immobilized transition nanoparticles with formates as an alternative to carbon monoxide. Herein we communicate our preliminary results.

In the beginning, we screened organic substrates that could be easily decarbonylated by transition metals. Aldehydes and formates can be good candidates for our purpose because they have been studied with this aim for three decades.^{7,9} We also chose ruthenium metal as a decarbonylation catalyst, stimulated by examples of recent use.^{4,7} Before using immobilized heterobimetallic ruthenium/cobalt nanoparticles as catalysts in the Pauson–Khand reaction, we tested the use of a combination of Ru₃(CO)₁₂ and cobalt nanoparticles with cinnamaldehyde, benzyl formate, or pyridylmethyl formate instead of carbon monoxide in the Pauson–Khand reaction. Recently, Shibata *et al.* reported^{6a,b} that both decarbonylation and the Pauson–Khand reaction could be catalyzed by the same rhodium complex and the carbon monoxide generated by the decarbonylation of an aldehyde was efficiently used as a CO source

for Pauson–Khand reactions. As part of this study we found that the expected Pauson–Khand reaction product was obtained in a high yield when pyridylmethyl formate was used with Ru₃(CO)₁₂ and cobalt nanoparticles (entry 1 in Table 1), but no reaction product was obtained when cinnamaldehyde or benzyl formate was used. This result may be ascribed to the chelation-accelerated decarbonylation of pyridylmethyl formate as suggested by Chang.⁷ Thus, we decided to use pyridylmethyl formate instead of CO. As expected, when either ruthenium carbonyl or colloidal cobalt nanoparticles (entries 2 and 3) were used as the catalyst in the presence of pyridylmethyl formate, no reaction product was obtained. The successful initial result encouraged us to make heterobimetallic ruthenium/cobalt nanoparticles immobilized on charcoal (**RuCNC**) and use them as catalysts in the Pauson–Khand reaction. These were prepared and characterized by TEM (Fig. 1).†

We investigated the use of **RuCNC** as a catalyst in the intramolecular Pauson–Khand reaction‡ under the same reaction conditions as applied to the Pauson–Khand reaction catalyzed by Ru₃(CO)₁₂/cobalt nanoparticles. **RuCNC** was also quite an effective catalyst for the intramolecular Pauson–Khand reaction. The yield was dependent upon the reaction time. As the reaction time increased from 3 to 18 h (entries 4–7), the yield increased from 40 to 98%. The optimized reaction conditions were established as follows: 1.5 equiv 2-pyridylmethyl formate, THF, 12 h, and 130 °C. Interestingly, when the reactor was

Table 1 Pauson–Khand-type reactions^a



Entry	Catalyst	Time/h	Yield (%) ^b
1	Ru ₃ (CO) ₁₂ /CNC	18	98
2	Ru ₃ (CO) ₁₂	18	—
3	CNC ^c	18	—
4	RuCNC ^d	18	98
5	RuCNC	12	97
6	RuCNC	6	73
7	RuCNC	3	40
8	Recovered from #5	12	98
9	Recovered from #8	12	98
10	Recovered from #9	12	97
11	Recovered from #10	12	97

^a Reaction conditions: 2-pyridylmethyl formate (1.5 eq), THF, 130 °C.

^b Isolated yields. ^c Cobalt nanoparticles—immobilized on charcoal (CNC).

^d Ruthenium and cobalt nanoparticles—immobilized on charcoal (**RuCNC**).

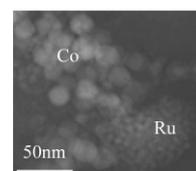
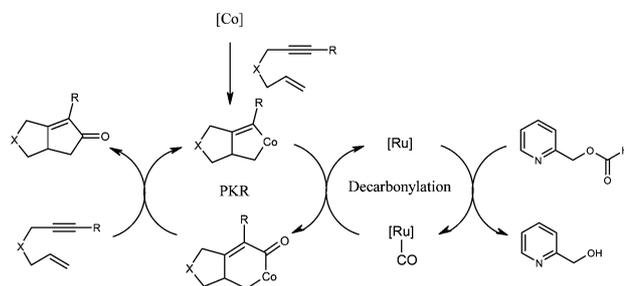


Fig. 1 TEM image of **RuCNC**.

filled with nitrogen, a higher yield was obtained. The most important advantage of heterogeneous catalysis over its homogeneous counterpart is the possibility of recovering the catalyst after reaction by simple filtration. For the intramolecular Pauson–Khand reaction, the catalyst system could be re-used five times without loss of activity (entries 8–11); the maximum reusability has not yet been tested. The reusability can be understood when we consider that there is almost no bleeding of cobalt and ruthenium from the charcoal surface. Elemental analysis (by ICP-AES) of the reaction mixture after completion of the reaction showed that less than 0.1 ppm of ruthenium and cobalt species were bled. Interestingly, when a Pauson–Khand reaction was carried out in the presence of ruthenium nanoparticles under 20 atm CO,¹⁰ a considerable quantity of ruthenium metal was bled presumably due to the formation of Ru₃(CO)₁₂.¹¹

The scope of the Ru/Co nanoparticle catalyst was examined with a number of substrates in both inter- and intramolecular Pauson–Khand-type reactions. Several representative results obtained under standard conditions are given in Table 2. The intramolecular cycloaddition proceeded smoothly with mono-substituted olefins (entries 1–4). Heteroatom-bridged enynes produced oxo- (entries 5 and 6) and azabicyclic compounds (entry 7) from the corresponding substrates. In most cases, the yields of the intramolecular reactions are almost quantitative. For intermolecular cycloadditions with the Ru/Co nanoparticle catalyst, satisfactory results are obtained with simple terminal alkynes (entries 8–10), a conjugated alkyne (entry 11), and a diyne (entry 12). In the case of the diyne substrate, a double Pauson–Khand reaction occurred. A plausible reaction mechanism for this overall process is depicted in Scheme 1.

In conclusion, Ru/Co nanoparticles on charcoal have been developed as highly effective catalysts for intra- and intermolecular Pauson–Khand-type reactions in the presence of



Scheme 1

pyridylmethyl formate instead of carbon monoxide. The reusability of the catalysts and the environmentally friendly process are especially attractive.

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Notes and references

† A solution of RuCl₃·nH₂O (1.0 g) in 20 mL ethylene glycol was heated at 180 °C for 0.5 h. After cooling, the solution was concentrated to ca. 10 mL. To the solution was added 100 mL of THF and flame-dried charcoal (2.0 g). The mixture was refluxed with colloidal cobalt in THF for 12 h. After the solution was filtered, the precipitate was washed successively with diethyl ether, dichloromethane, acetone, methanol, and dried *in vacuo*. TEM images of RuCNC revealed the cluster-in-cluster structure, with mean sizes of 5 and 18 nm for ruthenium and cobalt, respectively.

‡ To a solution of 1,6-enyne (0.20 g, 0.96 mmol) and pyridylmethyl formate (0.20 g, 1.45 mmol) was added RuCNC (0.10 g). The solution was heated at 130 °C for 12 h. After the solution was cooled to rt, the solution was filtered, concentrated, and chromatographed on a silica gel column eluting with hexane/diethyl ether (v/v, 5 : 1). When the catalyst was recycled, the catalyst was filtered, dried, and re-used for further catalytic reaction.

Table 2 Pauson–Khand reaction with various substrates.^a

Entry	Substrate	Product	Yield (%) ^b
1			75
2		R = H	97
3		R = CH ₃	98
4		R = Bu	93
5			91
6		R = CH ₃	97
7			89
8			90
9		R = Bu	93
10		R = TMS	90
11		R = Cyclohexen-1-yl	89
12			85

^a Reaction conditions : THF, 12 h, 130 °C. ^b Isolated yields.

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