DOI: 10.1002/asia.200800144

A Non-Cross-Linked Soluble Polystyrene-Supported Ruthenium Catalyst for Carbenoid Transfer Reactions

Matthew Kwok-Wai Choi,[a] Wing-Yiu Yu,[b] Man-Ho So,[a] Cong-Ying Zhou,[a]
Qing-Hai Deng,[a, c] and Chi-Ming Che*[a, c]

Dedicated to Professor Ryoji Noyori on the occasion of his 70th birthday

Abstract: Ruthenium nanoparticles supported on non-cross-linked soluble polystyrene were prepared by reacting $[RuCl_2(C_6H_5CO_2Et)]_2$ with polystyrene in open air. They effectively catalyze intra- and intermolecular carbenoid insertion into C–H and N–H bonds, alkene cyclopropanation, and ammonium ylide/[2,3]-sigmatropic rearrangement reactions. This supported ruthenium catalyst is much more reactive than $[RuCl_2(p\text{-cymene})]_2$ and [Ru(Por)CO] for catalytic intermolecular carbenoid C–H bond insertion into saturated alkanes. By using α-diazoacetamide as a substrate for intramolecular carbenoid C–H insertion, the supported ruthenium catalyst can be recovered and reused for ten successive iterations without significant loss of activity.

Keywords: carbenoid · catalysis · nanoparticles · ruthenium · soluble polymers

Introduction

Transition-metal-mediated carbenoid transfer and insertion reactions are useful for the construction of carbon–carbon and carbon–heteroatom bonds.[1] Rhodium(II),[2] copper(I),[3] and ruthenium(II)[4] complexes have been proven to be effective catalysts for the decomposition of diazo compounds to generate reactive metallocarbene intermediates, which are directly responsible for these catalytic X–H bond formation reactions (X = C, Si, N, P, O, halides).[1–4] Previously we found that $[RuCl_2(p\text{-cymene})]_2$ can effectively catalyze intramolecular carbenoid C–H insertion of α-diazoacetamides to *cis*-β-lactams with yields up to 97 %.[5] We also reported the synthesis of poly(ethylene glycol) (PEG)-supported ruthenium porphyrin complexes, which are suitable catalysts for epoxidation, cyclopropanation, and aziridination of alkenes.[6] However, these PEG-supported ruthenium porphyrin complexes are inactive toward intra- and intermolecular carbenoid C–H insertion reactions.

In the context of developing catalytic carbenoid transfer reactions with practical applications, immobilization of metal catalysts on a solid support is a commonly employed strategy. The immobilization of rhodium(II),[7–9] copper(I),[10] and ruthenium(II)[11] complexes on solid supports for heterogeneous catalytic carbenoid transfer reactions have been reported. In contrast, reports of carbenoid transfer to C=C bonds and insertion into C–H bonds employing metal catalysts supported on soluble polymer, which are bona fide homogeneous catalysis, are sparse.[12] In this area, we are interested in non-cross-linked polystyrene (NCPS), which is commercially available, has the advantage of homogeneous solution chemistry (high reactivity and ease of analysis), and at the same time allows easy isolation and purification of the organic products.[13]

Immobilization of a metal catalyst on polystyrene by microencapsulation was previously reported by Kobayashi and Akiyama.[14] This immobilization strategy does not require

---

[a] M. K.-W. Choi, M.-H. So, Dr. C.-Y. Zhou, Q.-H. Deng,
Prof. C.-M. Che
Department of Chemistry and Open Laboratory of Chemical Biology
Institute of Molecular Technology for Drug Discovery and Synthesis
The University of Hong Kong, Pokfulam Road, Hong Kong (China)
Fax: (+852) 2857-1586
E-mail: cmche@hku.hk

[b] Dr. W.-Y. Yu
Department of Applied Biology and Chemical Technology
The Hong Kong Polytechnic University
Hung Hom, Kowloon, Hong Kong (China)

[c] Q.-H. Deng, Prof. C.-M. Che
Shanghai–Hong Kong Joint Laboratory in Chemical Synthesis
Shanghai Institute of Organic Chemistry
The Chinese Academy of Sciences
354 Feng Lin Road, Shanghai 200032 (China)

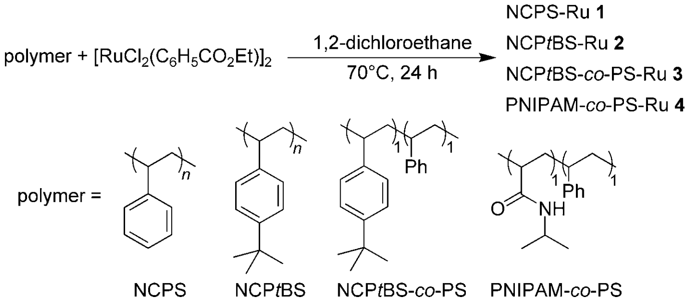
Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/asia.200800144.

ligand derivatization, allowing a convenient synthesis of polymer-supported metal catalysts. Herein we report that NCPS is an excellent carrier of ruthenium nanoparticles and that the resulting polymer-supported ruthenium nanoparticles are effective homogeneous catalysts for carbenoid transfer reactions with high substrate conversion and product turnover. This supported ruthenium catalyst shows good solubility in tetrahydrofuran, dichloromethane, chloroform, benzene, ethyl acetate, and toluene, but is insoluble in hexane and methanol. It can be recovered, and its reuse has been demonstrated in catalytic intramolecular carbenoid C–H insertion reactions for ten iterations without loss of activity.

Results

Synthesis and characterization

Preparation of the polymer-supported ruthenium catalyst NCPS-Ru **1** was undertaken by heating a mixture of non-cross-linked polystyrene (NCPS, 0.50 g) and $[RuCl_2(C_6H_5CO_2Et)]_2$ (0.10 g) in 1,2-dichloroethane (10 mL) in open atmosphere (Scheme 1). When the reaction was monitored by ^1H NMR spectroscopy, the ^1H signals of $[RuCl_2(C_6H_5CO_2Et)]_2$ disappeared, and that of ethyl benzoate concomitantly developed, revealing the grafting of ruthenium atoms and/or ions by the phenyl rings of polystyrene.[15] No significant change in the ^1H NMR spectrum of NCPS was observed, owing to the low portion of polystyrene phenyl rings that contribute to the grafted ruthenium atoms and ions. The ruthenium content of NCPS-Ru **1** was determined to be 5.0 wt % using inductively coupled plasma spectroscopy (ICP), and hence the loading was 0.50 mmol g^{-1}. Other soluble polymer supports such as poly(*tert*-butylstyrene) (NCP*t*BS),[16] poly(*tert*-butylstyrene-*co*-styrene) (NCP*t*BS-*co*-PS),[16] and poly(*N*-isopropylacrylamide-*co*-styrene) (PNIPAM-*co*-PS)[17] were used to react with $[RuCl_2(C_6H_5CO_2Et)]_2$ in 1,2-dichloroethane to give the corresponding soluble polymer-supported ruthenium catalysts as depicted in Scheme 1.



Scheme 1. Synthesis of polymer-supported ruthenium catalysts **1**–**4**.

Examination of NCPS-Ru **1** by transmission electron microscopy (TEM) showed the presence of uniform spherical ruthenium nanoparticles (Figure 1 a) with an average diameter of 1.72±0.17 nm and a monodispersity of 9.9 % (Figure 1 b). Selected area electron diffraction (SAED) showed two broad diffraction rings, which can be indexed back to metallic Ru (JCPDS no. 06-0663) (Figure 1 c). High-resolution TEM imaging showed clear lattice fringes, which reveal that the ruthenium nanoparticles were single-crystallized (Figure 1 d). The d-spacing was 2.047 Å corresponding to the (101) plane of metallic ruthenium crystals.

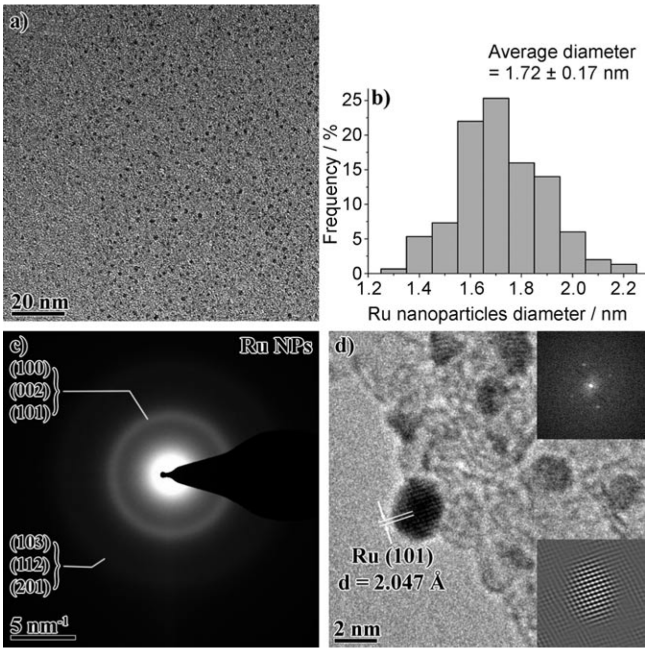


Figure 1. a) TEM images of Ru nanoparticles. b) Histogram showing the distribution of the Ru nanoparticle diameters. c) SAED pattern of the Ru nanoparticles. d) High-resolution TEM image of a single Ru nanoparticle, with lattice fringes clearly apparent; top right insert: FFT image of the particle; bottom right insert: nanoparticle TEM image filtered with the Gatan Digital Micrograph program.

Energy-dispersive X-ray spectroscopy (EDX) mapping of NCPS-Ru **1** revealed that the Ru nanoparticles are distributed evenly inside the polymer (Figure 2 and figure S1, Supporting Information). X-ray photoelectron spectroscopic (XPS) analysis of freshly prepared NCPS-Ru **1** catalyst showed a peak at 463.9 eV, corresponding to Ru $3p_{3/2}$ binding energy (Figure 3). This value slightly deviates from the reported value of bulk Ru metal (462.0 eV)[18] and $[RuCl_2(C_6H_5CO_2Et)]_2$ (462.5 eV), revealing that the polymer-supported ruthenium nanoparticles contain surface-oxidized ruthenium ions.

Intramolecular carbenoid transfer and insertion reactions

All polymer-supported ruthenium catalysts **1**–**4** were examined for intramolecular carbenoid C–H insertion of *N*-*p*-chlorobenzyl-*N*-*tert*-butyl-α-ethoxycarbonyl-α-diazoacetamide **5a** (Table 1). The reaction was performed in toluene at 70 °C in an open atmosphere. Using NCPS-Ru **1** (1.0 mol % Ru relative to substrate), the diazo compound was completely consumed within 1 h, and *cis*-β-lactam was exclusive-

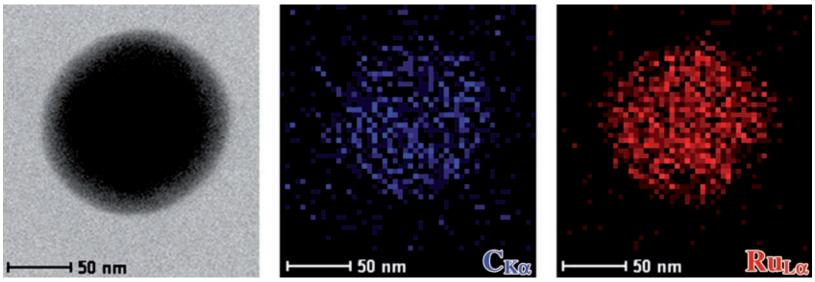


Figure 2. Scanning transmission electron microscopy (STEM) image of a single NCPS-Ru nanoparticle and the corresponding EDX maps of $C_{K\alpha}$ and $Ru_{L\alpha}$ signals (the TEM image at left is at approximately the same point of the mapping).

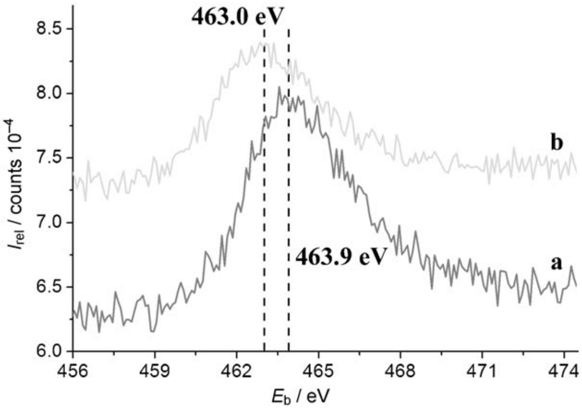
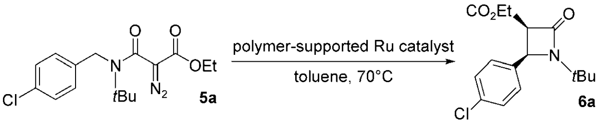


Figure 3. XPS spectra of NCPS-Ru **1** (trace a) and a sample prepared by allowing NCPS and $[RuCl_2(C_6H_5CO_2Et)]_2$ to react in the presence of $NaBH_4$ in 1,2-dichloroethane (trace b).

Table 1. Effect of polymer-supported ruthenium catalysts on intramolecular carbenoid C−H insertion of α-diazoacetamides.



Entry	Catalyst	*t* [h]	Conv [%][a]	Yield [%][b]	*cis*/*trans*[c]
1	NCPS-Ru **1**	1	100	98	>99:1
2	NCP*t*BS **2**	4	63	91	95:5
3	NCP*t*BS-*co*-PS **3**	4	50	89	95:5
4	PINAM-*co*-PS **4**	4	50	89	95:5

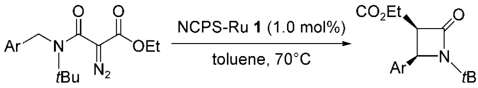
[a] Conversion was determined by ^{1}H NMR analysis of the reaction mixture using 1,1-diphenylethene as internal standard. [b] Yield of *cis*-β-lactams was determined by ^{1}H NMR analysis of the reaction mixture using 1,1-diphenylethene as internal standard. [c] The *cis*/*trans* ratio was determined by ^{1}H NMR analysis of the reaction mixture.

ly formed in 98% yield. This catalysis was repeated four times with independently prepared samples of NCPS-Ru catalyst with a Ru content of 5.0 wt%, and similar results were obtained (98% yield of *cis*-β-lactam). As depicted in Table 1, catalysts **2**, **3**, and **4** showed lower catalytic activities manifested by 50–60% substrate conversion over the course of 4 h.

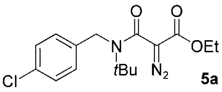
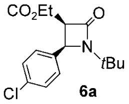
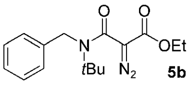
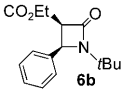
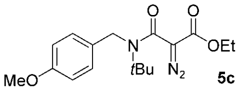
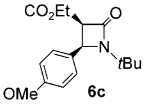
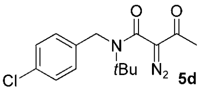
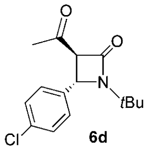
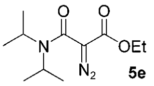
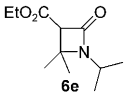
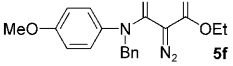
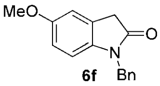
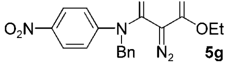
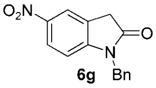
Toluene, ethyl acetate, and acetone were found to be the most effective solvents for the cyclization of **5a** to give *cis*-β-lactam (up to 99% yield) and with complete *cis*-selectivity (see table S1 in Supporting Information). Incomplete substrate conversion (5–60%) was observed with the use of tetrahydrofuran, *N*,*N*-dimethylformamide (DMF), or dichloromethane as solvent.

The substrate scope of the intramolecular carbenoid C−H insertion was examined, and the results are listed in Table 2. The stereoselectivity of the NCPS-Ru-catalyzed reactions (1.0 mol% Ru relative to substrate) is similar to the analogous reactions with the homogeneous $[RuCl_2(p\text{-cymene})]_2$ catalyst.[5] For example, effective transformation of α-diazoacetamides with various aryl groups into the corresponding *cis*-β-lactams were carried out in yields of >90% (Table 2, Entries 2 and 3). With α-diazo-

Table 2. NCPS-Ru-catalyzed intramolecular carbenoid C−H insertion of α-diazoacetamides.[a]



(1)

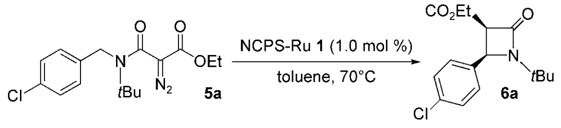
Entry	Substrate	Product	Yield [%][b]
1	 **5a**	 **6a**	98
2	 **5b**	 **6b**	90
3	 **5c**	 **6c**	91
4	 **5d**	 **6d**	93
5	 **5e**	 **6e**	89
6	 **5f**	 **6f**	93
7	 **5g**	 **6g**	78

[a] A mixture of diazo compound (1.0 mmol) and NCPS-Ru **1** (1.0 mol%) was stirred in toluene at 70°C. [b] Values indicate isolated yield.

ketone as substrate, the NCPS-Ru-catalyzed carbenoid C−H insertion produced *trans*-β-lactam in 93 % yield (Table 2, Entry 4). For *N*,*N*-diisopropyl-substituted α-diazoacetamide **5e**, the carbenoid C−H insertion was directed to the methine (3°) C−H bond, furnishing β-lactam in 89 % isolated yield (Table 2, Entry 5). Interestingly, with α-diazoanilides containing an electron-donating (OMe) or electron-withdrawing group (NO$_2$), only intramolecular carbenoid C−H insertion into the phenyl group was observed, and the corresponding γ-lactams were isolated in good to excellent yields (Table 2, Entries 6 and 7). Reaction (1) could be performed at the preparative gram scale (4.0 g substrate) with 1.0 mol % NCPS-Ru **1** catalyst; *cis*-β-lactam (3.3 g) was obtained in 90 % yield in a one-pot cyclization of *N*-*p*-chlorobenzyl-*N*-*tert*-butyl-α-ethoxycarbonyl-α-diazoacetamide.

The NCPS-Ru **1** catalyst was subjected to ten successive reactions under the conditions: NCPS-Ru **1** (1.0 mol %) and diazo compound (1.0 mmol) in toluene at 70 °C in an open atmosphere. Upon completion of the reaction, hexane (2 mL) was added to induce precipitation of the polymer. After centrifugation, the organic product was separated from the mixture by decantation. The reaction vessel containing the Ru-grafted polymer was recharged with diazo compound and toluene (2 mL) for consecutive reactions. The results for recycling of the polymer-supported ruthenium catalyst for intramolecular carbenoid C−H insertions are listed in Table 3. After ten consecutive reactions, the recovered NCPS-Ru **1** catalyst was found to contain 5.0 wt % Ru (based on ICP analysis), which was essentially the same as the initial value. Therefore, there was no detectable catalyst leaching over the ten consecutive reactions.

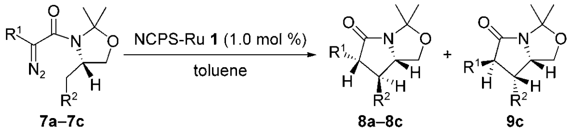
Table 3. Reusability of NCPS-Ru **1** in the intramolecular carbenoid C−H insertion reaction.[a]



Cycle	*t* [h]	Conv [%]	Yield [%][b]	Cycle	*t* [h]	Conv [%]	Yield [%][b]
1	0.5	100	97	6	0.5	100	94
2	0.5	100	94	7	0.5	100	93
3	0.5	100	99	8	0.5	100	95
4	0.5	100	98	9	0.5	100	97
5	0.5	100	96	10	0.5	100	94

[a] A mixture of diazo compound (1.0 mmol) and NCPS-Ru **1** (1.0 mol %) was stirred in toluene at 70 °C. [b] Yield of products was determined by ^{1}H NMR using 1,1-diphenylethene as internal standard.

Table 4. NCPS-Ru-catalyzed carbenoid C−H insertion of α-diazo compounds derived from various α-amino acids.[a]



Entry	R^1	R^2	Diazo Compd **7**	*T* [°C]	*t* [h]	**8**:**9**[c]	Yield [%][b]
1	EtO$_2$C	Ph	**7a**	70	48	**8a**	89
2	MeCO	Ph	**7b**	70	48	**9b**	90
3	MeCO	OTBS	**7c**	70	16	1:1	92
4	MeCO	OTBS	**7c**	40	48	1:2	89

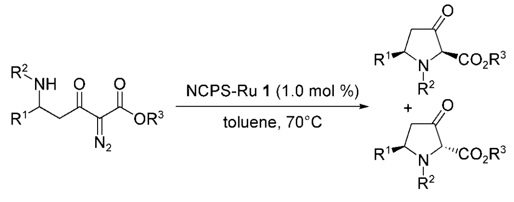
[a] A mixture of diazo compound (1.0 mmol) and NCPS-Ru **1** (1.0 mol %) was stirred in toluene at 70 °C. [b] Values indicate isolated yields. [c] The stereochemistry of **8** and **9** were characterized by a 2D NOESY NMR study.

Highly functionalized γ-lactams can be synthesized through catalytic carbenoid C−H insertion of diazoacetamides derived from amino acids.[19] The results using NCPS-Ru **1** as catalyst are listed in Table 4. Treatment of diazoacetamide **7a** prepared from L-phenylalanine with NCPS-Ru **1** as catalyst (1.0 mol %) gave *trans*,*trans*-γ-lactam **8a** in 89 % yield. (Table 4, Entry 1). The *trans*,*trans* stereochemistry was established by ^{1}H–^{1}H NOESY NMR analysis (see Supporting Information). Similarly, *trans*,*trans*-γ-lactam **8b** was obtained in 90 % yield using **7b** as substrate (Table 4, Entry 2). α-Diazoacetamide **7c**, which contains an electron-donating OTBS ether group, also underwent Ru-catalyzed cyclization to afford a 1:1 mixture of diastereomeric bicyclic lactams in 92 % yield (Table 4, Entry 3). When the reaction was performed at a lower temperature (40 °C), a mixture of diastereomers was obtained in an overall yield of 89 % and with a ratio of **8c**/**9c** = 1:2 (Table 4, Entry 4).

We also examined intramolecular carbenoid N−H insertion reactions[20] and cyclopropanation of allyl diazoacetates using NCPS-Ru **1** as catalyst. This catalyst can effectively catalyze intramolecular carbenoid N−H insertion to give the proline products with high *cis* selectivity and in excellent yields (91–96 %) as listed in Table 5.

The NCPS-Ru **1** catalyst is also active toward intramolecular cyclopropanation of allyl diazoacetates. Treatment of the allyl diazoacetates with the catalyst for 12 h led to the

Table 5. NCPS-Ru-catalyzed intramolecular carbenoid N−H insertion reaction.[a]

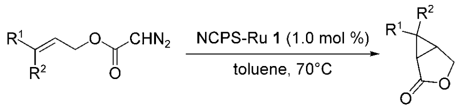


Entry	R^1	R^2	R^3	*t* [h]	*cis*/*trans*[c]	Yield [%][b]
1	Ph	*p*-BrPh	Et	4	18:1	95
2	Ph	*p*-OMePh	Et	4	20:1	96
3	*p*-ClPh	Ph	Et	4	14:1	92
4	*p*-OMePh	Ph	Et	4	16:1	94
5	*p*-MePh	Ph	Et	4	12:1	91
6	Ph	Ph	Et	4	10:1	92
7	Ph	Ph	Me	3	9:1	93

[a] A mixture of diazo compound (1.0 mmol) and NCPS-Ru **1** (1.0 mol %) was stirred in toluene at 70 °C. [b] Values indicate isolated yields. [c] The *cis*/*trans* ratio was determined by ^{1}H NMR analysis.

corresponding cyclopropyl lactones in good yields (70%–89%, see Table 6).

Table 6. NCPS-Ru **1** catalyzed intramolecular cyclopropanation of allyl diazoacetates.[a]

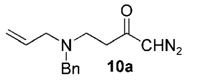
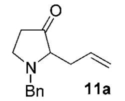
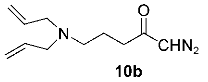
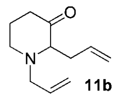
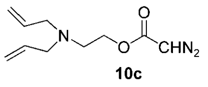
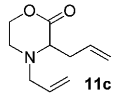


Entry	R^1	R^2	Yield [%][b]
1	H	H	86
2	CH_3	H	82
3	CH_3CH_2	H	83
4	Ph	H	89
5	H	Ph	70[c]
6	H	CH_3CH_2	70
7	CH_3	CH_3	85

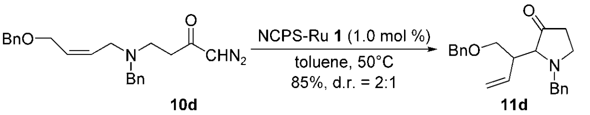
[a] A solution of allyl diazoacetate (1.0 mmol) was dropwise addition to NCPS-Ru **1** (1.0 mol%) in toluene at 70°C. [b] Isolated yield. [c] *syn*:*anti* = 4:1.

We also examined intramolecular tandem ammonium ylide/[2,3]-sigmatropic rearrangement reactions. Treatment of **10a** with NCPS-Ru **1** (1.0 mol%) afforded [2,3]-sigmatropic rearrangement product **11a** in 92% yield with no [1,2]-rearrangement product detected (Table 7, Entry 1). This result is similar to that observed with [Ru^{II}(TTP)(CO)] as catalyst (H_2TPP = *meso*-tetraphenylporphyrin).[21] Similarly, diazoketone **10b** was found to undergo effective cyclization to give pyridone **11b** in 89% yield (Table 7, Entry 2), and diazoester **10c** was converted into morpholinone **11c** in 91% yield (Table 7, Entry 3). We previously reported that [Ru^{II}(TTP)(CO)]-catalyzed intramolecular ammonium ylide/[2,3]-sigmatropic rearrangement could be used as a key step for the synthesis of (±)-platynecine.[21] In the work reported herein, we found that with NCPS-Ru **1** as catalyst (1.0 mol%), a similar result (85% yield, d.r. = 2:1) was obtained (Scheme 2).

Table 7. NCPS-Ru-catalyzed intramolecular tandem ammonium ylide/[2,3]-sigmatropic rearrangement reactions.[a]

Entry	Substrate	Product	Yield [%][b]
1			92
2			89
3			91

[a] Diazo compound (1.0 mmol) was added dropwise to NCPS-Ru **1** (1.0 mol%) in toluene at 50°C. [b] Values indicate isolated yield.

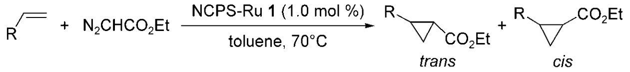


Scheme 2. Intramolecular tandem ammonium ylide/[2,3]-sigmatropic rearrangement reactions catalyzed by NCPS-Ru **1**.

Intermolecular carbenoid transfer and insertion reactions

The catalytic intermolecular alkene cyclopropanation and carbenoid N–H and C–H insertions using NCPS-Ru **1** as catalyst were examined. Catalyst **1** is active toward the intermolecular cyclopropanation of alkenes, as revealed by the results in Table 8.

Table 8. NCPS-Ru-catalyzed intermolecular cyclopropanation of alkene with ethyl diazoacetate.[a]



Entry	R	Yield [%][b]	*trans*/*cis*[c]
1	C_6H_5	91	70:30
2	*p*-Cl-C_6H_4	85	73:27
3	*p*-OMe-C_6H_4	90	68:32
4	*n*-butyl	67	70:30

[a] EDA (1.0 mmol) was added dropwise to a mixture of alkene (2.0 mmol) and NCPS-Ru **1** (1.0 mol%) in toluene at 70°C. [b] Values indicate isolated yield. [c] The *trans*/*cis* ratio was determined by ^{1}H NMR analysis.

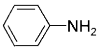
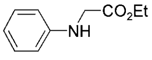
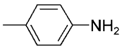
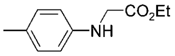
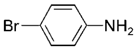
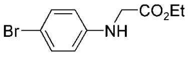
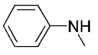
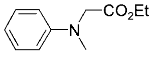
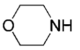
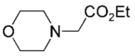
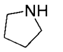
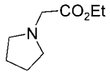
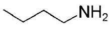
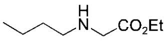
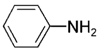
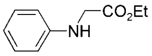
Carbenoid insertion into N–H bonds is a useful means for the synthesis of α-amino carboxylic compounds.[22] In this work, we found that the NCPS-Ru-catalyzed intermolecular carbenoid N–H insertion reactions could be performed without the use of a slow addition procedure or an inert atmosphere. The N–H insertion products were obtained in high yields by a one-pot reaction of amine and ethyl diazoacetate in toluene at 70°C in open atmosphere (that is, without Ar/N_2 protection). Complete substrate conversions were observed within 1 h (Table 9).

Most metal-catalyzed intermolecular carbenoid N–H insertion reactions are reported to have been conducted at the millimolar scale.[22] In this work, we examined the feasibility of scaling up the reaction between aniline and ethyl diazoacetate, using 0.1 mol substrate (Table 9, Entry 8). Ethyl diazoacetate (0.10 mol) was added in one portion to a mixture of aniline (0.11 mol) and NCPS-Ru **1** (0.1 mol%) in toluene at 70°C in open atmosphere. Complete substrate conversion was observed within 1 h. *N*-Phenylglycine ethyl ester was obtained in 97% yield. At a lower catalyst loading (0.01 mol%) the same reaction at the 0.1-mol scale required a longer reaction time (4 days) for complete consumption of ethyl diazoacetate, and no diazo coupling products (fumarate/malate) were detected by ^{1}H NMR analysis of the reaction mixture. *N*-Phenylglycine ethyl ester was obtained in 93% yield.

Intermolecular carbenoid C–H insertion of saturated alkanes is difficult to carry out,[23] and there are no published

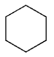
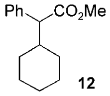
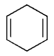
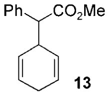
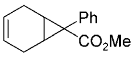
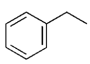
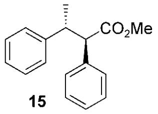
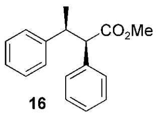
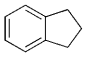
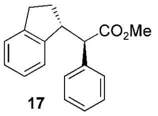
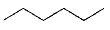
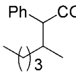
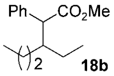
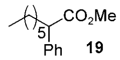
Table 9. NCPS-Ru-catalyzed intermolecular N–H insertion of amine with ethyl diazoacetate.[a]

$$RNH_2 + N_2CHCO_2Et \xrightarrow[\text{toluene, 70°C}]{\text{NCPS-Ru}} RNHCH_2CO_2Et$$

Entry	Substrate	Product	Yield [%][b]
1			99
2			97
3			97
4			83
5			91
6			89
7			60
8[c]			93

[a] EDA (1.0 mmol) was added in one portion to a mixture of amine (1.1 mmol) and NCPS-Ru **1** (1.0 mol %) in toluene at 70 °C. [b] Values indicate isolated yield. [c] EDA (0.10 mol) was added in one portion to a mixture of aniline (0.11 mol) and NCPS-Ru **1** (0.1 mol %) in toluene at 70 °C.

Table 10. Intermolecular C–H insertion of hydrocarbons with methyl phenyl diazoacetate catalyzed by NCPS-Ru **1**.[a]

Entry	Substrate	Product	Yield [%][b]
1		 **12**	60
2[c]		 **13**  **14**	66 (4:1)
3		 **15**  **16**	63 (1.2:1)
4		 **17**	62
5		 **18a**  **18b**  **19**	50[d]

[a] A mixture of diazo compound (1.0 mmol) and NCPS-Ru **1** (1.0 mol %) was stirred in neat substrate at 70 °C. [b] Values indicate isolated yield. [c] Toluene as solvent. [d] (**18a**+**18b**)/**19** = 5:1.

reports on the use of ruthenium complexes to effectively catalyze intermolecular carbenoid insertion into C–H bonds of saturated alkanes. In this work, we investigated NCPS-Ru-catalyzed intermolecular carbenoid C–H insertion reactions, and the results are depicted in Table 10. The reaction of methyl phenyl diazoacetate with neat cyclohexane in the presence of NCPS-Ru **1** (1.0 mol %) afforded the C–H insertion product **12** in 60 % yield. Similarly, the NCPS-Ru-catalyzed reaction of methyl phenyl diazoacetate with 1,4-cyclohexadiene furnished the C–H insertion product **13** and cyclopropanated product **14** at a ratio of 4:1 in 66 % overall yield (Table 10, Entry 2). With ethylbenzene, a 1.2:1 mixture of C–H insertion products was obtained in 63 % overall yield (Table 10, Entry 3).[24] The reaction of indane with methyl phenyl diazoacetate gave **17** as a single isomer in 62 % yield (Table 10, Entry 4). With *n*-hexane as substrate, the secondary (compounds **18a** and **18b**) to primary (compound **19**) C–H insertion products were formed in a ratio of 5:1 (Table 10, Entry 5).

Discussion

Polymer-supported catalysts for carbenoid transfer and insertion reaction

Transition-metal-catalyzed carbenoid transfer reactions are useful tools for the construction of carbon–carbon and carbon–heteroatom bonds.[1–4] However, a main obstacle in the development of the practical applications of transition-metal-catalyzed carbenoid transfer and insertion reactions is catalyst recovery and recycling. In this regard, supported metal catalysts have the advantages of easy recovery. There have been extensive reported studies on the immobilization of ligands and metal complexes on polymer supports.[25]

The first polymer-supported heterogeneous catalyst for carbenoid transfer was reported by Doyle and co-workers. Dirhodium(II) tetrakis(methyl-2-oxapyrrolidine-(5*S*)-carboxylate (Rh_2((5-*S*)-MEPY) supported on NovaSyn Tentagel (TG) hydroxy resin and the Merrifield resin was achieved through the formation of an ester linkage to one of the pyrrolidinone ligands. This immobilized Rh catalyst was tested in intra- and intermolecular alkene cyclopropanation and intramolecular carbenoid C–H insertion reactions.[7] In 2002, Davies and co-workers immobilized a dirhodium tetraprolinate complex on a polymer through coordination of $Rh_2(S\text{-DOSP})_4$, $Rh_2(S\text{-TBSP})_4$, or $Rh_2(S\text{-biTISP})_4$ to the pending pyridyl groups of the polymer support. These immobilized catalysts have been tested in asymmetric intra- and intermolecular cyclopropanation of alkenes with methyl phenyl diazoacetate and intra- and intermolecular carbenoid C–H insertion reactions using donor/acceptor-substituted carbenoids.[8]

Although heterogeneous catalysis offer the advantages of simple product separation, isolation and catalyst reuse, paradoxically several issues remain to be addressed, such as nonlinear kinetic behavior, unequal distribution/access to active sites, and problems of solubility.[13c] The use of soluble polymers as support for recyclable catalysts and reagents has received considerable attention.[11] Soluble polymer-supported metal catalysts exhibit similar features (such as reactivity, catalytic activity, enantioselectivity, and stereoselectivity) to their analogous homogeneous counterparts.[13] Among many soluble polymer supports, non-cross-linked polystyrene (NCPS) is a common soluble polymer which is commercially available. It has the advantages of homogeneous solution chemistry (high reactivity and ease of analysis) and those of solid-phase methods (ease of isolation and purification of products).[13] NCPS was first used as a support for peptide synthesis.[26] It has recently been used in a range of application studies, including use as a support for catalysts and reagents.[27] Reactions with NCPS-supported metal catalysts have been summarized in a review article.[28]

There are few reported examples on the use of soluble polymer-supported catalysts for carbenoid transfer reactions. Doyle and Bergbreiter used a polyethylene-supported dirhodium(II) 2-pyrrolidinone-5(*S*)-carboxylate catalyst for intramolecular alkene cyclopropanation and intramolecular C−H insertion reactions, and high enantioselectivities were observed in some of these reactions.[12a] We have also developed a PEG-supported ruthenium porphyrin catalyst for the cyclopropanation of alkenes.[6] Bergbreiter and co-workers recently reported a polyisobutylene-supported rhodium carboxylate and bisoxazoline copper trifluoromethanesulfonyl complex for the cyclopropanation of alkenes.[12b]

Soluble polymer-supported ruthenium nanoparticles

Kobayashi and Akiyama reported the use of microencapsulation as a technique to immobilize metal complexes by π interactions between the phenyl rings of a polystyrene-based polymer and metal ions.[14] Such supported metal catalysts have been used in a variety of reactions such as [MC-Sc(OTf)$_3$] in aza Diels–Alder, Strecker reactions, cyanation and alkylation,[14] Mannich-type and aldol reactions,[29] and silylation of alcohols;[30] microencapsulated osmium tetroxide [MC-OsO$_4$] for dihydroxylation of alkenes;[31] and [MC-Pd(PPh$_3$)] for allylic substitution, Suzuki coupling, and Mizoroki–Heck reactions.[32] Recently, Kobayashi and co-workers reported highly active and recyclable microencapsulated gold nanoclusters as catalysts for the aerobic oxidation of alcohols at room temperature under atmospheric conditions.[33] This is the first example of the stabilization of metal nanoclusters by interaction with the phenyl rings of polystyrene.

In the work reported herein, we found that NCPS-Ru **1** could be prepared in quantitative yield by heating a mixture of NCPS and [RuCl$_2$(C$_6$H$_5$CO$_2$Et)]$_2$ in 1,2-dichloroethane. Examination of NCPS-Ru **1** by TEM revealed the presence of uniform ruthenium nanoparticles supported on the polymer. XPS analysis of a freshly prepared polymer-supported ruthenium catalyst showed a peak at 463.9 eV, which deviates slightly from the reported value of bulk Ru metal (462.0 eV)[17] and [RuCl$_2$(C$_6$H$_5$CO$_2$Et)]$_2$ (462.5 eV). This result suggests that the surface of the Ru nanoparticles is probably coated with oxidized Ru^{n+} ions.

The role of oxidized Ru^{n+} ions in reactions mediated by the NCPS-Ru catalyst was revealed by the following sets of experiments: We attempted to prepare a related polymer-supported ruthenium catalyst by reduction of RuCl$_3$·nH$_2$O with NaBH$_4$[34] in the presence of NCPS. However, the resulting polymer was found to contain <0.1 wt % Ru based on ICP analysis. We also attempted to prepare polymer-supported ruthenium nanoparticles by reacting NCPS, [RuCl$_2$(C$_6$H$_5$CO$_2$Et)]$_2$, and NaBH$_4$ in 1,2-dichloroethane under an argon atmosphere, and the resulting polymer-supported catalyst was characterized by TEM. XPS analysis of this freshly prepared polymer-supported ruthenium catalyst showed a peak at 463.0 eV, which is slightly lower than the peak at 463.9 eV for the NCPS-Ru **1** (Figure 3). We suggest that the surface charge of the ruthenium nanoparticles may be reduced by NaBH$_4$. Importantly, this polymer-supported ruthenium catalyst effected <5 % substrate conversion for the cyclization of **5a** over a reaction time of 4 h. When the reaction was conducted in 1,2-dichloroethane at 70 °C with a continuous oxygen flow at atmospheric pressure, an equimolar mixture of *cis* and *trans*-β-lactams with complete substrate conversion was obtained after 4 h in 88 % overall yield. Altogether, these results reveal that the oxidized ruthenium ions of the polymer-supported ruthenium nanoparticles played a key role in the carbenoid transfer reactions.

To examine the role of [RuCl$_2$(C$_6$H$_5$CO$_2$Et)]$_2$ complex in the preparation of NCPS-supported ruthenium nanoparticles, several ruthenium precursors such as [RuCl$_2$(*p*-cymene)]$_2$, RuCl$_3$·nH$_2$O, and Ru$_3$(CO)$_{12}$ were used. These Ru precursors were individually reacted with NCPS in 1,2-dichloroethane at 70 °C in open atmosphere (that is, without Ar/N$_2$ protection). However, the resulting polymers contained <0.1 wt % Ru based on ICP analysis. These polymers were also screened for the intramolecular carbenoid C−H insertion reaction of **5a**. However, only the polymer-supported ruthenium catalyst prepared from [RuCl$_2$(C$_6$H$_5$CO$_2$Et)]$_2$ displayed the highest activity and stereoselectivity, affording *cis*-β-lactam in 98 % yield under the following conditions: 1.0 mol % Ru relative to substrate, toluene, 1 h, 70 °C. Other polymer-supported catalysts were fruitless (<10 % conversion).

Previously published hydroxyapatite-supported[35] and graphite-supported ruthenium nanoparticles (see figure S2 in Supporting Information) were prepared and examined for their catalytic activities toward carbenoid C−H insertion using **5a** as a substrate. Employing the reaction conditions: 1.0 mol % Ru relative to substrate, toluene, 1 h, 70 °C, these two supported ruthenium catalysts failed to catalyze cyclization of **5a**.

Chang and co-workers reported the use of [RuCl$_2$(*p*-cymene)]$_2$ as catalyst in Heck-type olefination reactions for a wide range of alkenes and aryl iodide in the presence of sodium acetate in DMF at 135 °C.[36] Under the reaction conditions: [RuCl$_2$(*p*-cymene)]$_2$ (5.0 mol %), NaOAc (1.0 mmol), **5a** (1.0 mmol), DMF (1 mL), cyclization of **5a** failed with complete recovery of the starting materials after a reaction time of 4 h.

We were delighted to find that the activity of NCPS-Ru **1** is superior to that of [RuCl$_2$(*p*-cymene)]$_2$. Using NCPS-Ru **1** as catalyst, efficient carbenoid C–H insertion of diazoacetamides derived from amino acids was achieved, resulting in bicyclic γ-lactams. For example, **7a** and **7b** were efficiently converted into γ-lactam **8a** (89 %) and **8b** (90 %), respectively, in contrast to the similar reaction catalyzed by $[RuCl_2(p\text{-cymene})]_2$, which gave only <10 % product yield. Notably, NCPS-Ru **1** can also catalyze intermolecular carbenoid C–H bond insertion reactions, whereas $[RuCl_2(p\text{-cymene})]_2$ does not (Table 10). This is the first example of a ruthenium catalyst used for intermolecular carbenoid C–H insertion of saturated alkanes.

Conclusions

Soluble polymer-supported ruthenium nanoparticles can be conveniently prepared by treating $[RuCl_2(C_6H_5CO_2Et)]_2$ with NCPS. Ruthenium nanoparticles were found to disperse well on the phenyl rings of polystyrene. This supported ruthenium catalyst efficiently catalyzes intra- and intermolecular carbenoid insertions into C–H and N–H bonds, alkene cyclopropanations, and ammonium ylide/[2,3]-sigmatropic rearrangements.

Experimental Section

General: $[RuCl_2(C_6H_5CO_2Et)]_2$ was synthesized by published methods.[37] Toluene was freshly distilled from sodium/benzophenone under a nitrogen atmosphere. Flash chromatography was performed on silica gel (Merck Kieselgel 60, 230–400 mesh). ^1H and ^{13}C NMR spectra were recorded on Bruker DPX-300, -400, and -500 spectrometers. Chemical shifts (δ, ppm) were determined with TMS as internal reference. MS data were obtained on a Finnigan MAT 95 mass spectrometer. IR spectra (ν, cm^{-1}) were recorded on a BioRad PTS-165 spectrometer. TEM was carried out on a Philips Tecnai G2 20 S-TWIN instrument with an accelerating voltage of 200 kV. The TEM images were taken with a Gatan Multi-Scan Camera Model 794. EDX analysis was performed on an Oxford Instruments Inca with a scanning range from 0 to 20 keV. Scanning electron microscopy (SEM) images were taken on a LEO 1530 FEG instrument operating at 5 kV. XPS measurements were performed on a Physical Electronic 5PHI 5600 instrument with a monochromatic $Al_{K\alpha}$ X-ray source. TEM samples were prepared by placing a drop of a freshly prepared solution of NCPS-Ru **1** onto the formvar-coated copper grids, which were then dried in a vacuum desiccator.

General procedure I: preparation of polymer-supported ruthenium catalysts (1–4)

NCPS-supported Ru catalyst 1. A mixture of NCPS (0.50 g) and $[RuCl_2(C_6H_5CO_2Et)]_2$ (0.10 g, 0.16 mmol) in 1,2-dichloroethane (30 mL) was stirred at 70 °C for 24 h. The solution was concentrated in vacuo. The residue was taken up in 5 mL 1,2-dichloroethane. This solution was added dropwise to vigorously stirred cold hexane (200 mL). The black precipitate was filtered and dried to afford NCPS-Ru **1** as a black powder (0.58 g, ~100 %). The loading of Ru was determined to be 0.50 $mmol\,g^{-1}$ by ICP analysis.

Preparation of non-cross-linked poly(*tert*-butylstyrene)-supported Ru catalyst 2. A mixture of poly(*tert*-butylstyrene) (0.50 g) and $[RuCl_2(C_6H_5CO_2Et)]_2$ (0.10 g) in 1,2-dichloroethane (30 mL) was stirred at 70 °C for 24 h. Using the same procedure as described above, NCP*t*BS-Ru **2** was obtained as a black powder (0.57 g, ~100 %). The loading was determined to be 0.45 $mmol\,g^{-1}$ by ICP analysis.

Preparation of non-cross-linked poly(*tert*-butylstyrene-*co*-styrene)-supported Ru catalyst 3. A mixture of poly(*tert*-butylstyrene-*co*-styrene) (0.50 g) and $[RuCl_2(C_6H_5CO_2Et)]_2$ (0.10 g) in 1,2-dichloroethane (30 mL) was stirred at 70 °C for 24 h. Using the same procedure as described above, NCP*t*BS-*co*-PS-Ru **3** was obtained as a black powder (0.56 g, ~100 %). The loading was determined to be 0.41 $mmol\,g^{-1}$ by ICP analysis.

Preparation of non-cross-linked poly(*N*-isopropylacrylamide-*co*-styrene)-supported Ru catalyst 4. A mixture of poly(*N*-isopropylacrylamide-*co*-styrene) (0.50 g) and $[RuCl_2(C_6H_5CO_2Et)]_2$ (0.10 g) in 1,2-dichloroethane (30 mL) was stirred at 70 °C for 24 h. Using the same procedure as described above, PNIPAM-*co*-PS-Ru **4** was obtained as a black powder (0.56 g, ~100 %). The loading was determined to be (0.40 $mmol\,g^{-1}$) by ICP analysis.

General procedure II: NCPS-Ru-catalyzed intramolecular carbenoid C–H insertion reaction of α-diazoacetamide

A mixture of diazo compound (1.0 mmol) and NCPS-Ru **1** (1.0 mol %) was stirred in toluene (2 mL) at 70 °C. The reaction was monitored by TLC analysis (20 % EtOAc/hexane) for complete consumption of the diazo starting material. Upon addition of hexane (2 mL) the reaction mixture was centrifuged, and aliquots were taken from the supernatant for product identification and quantitation by ^1H NMR spectroscopy. To obtain pure product, the supernatant was separated and evaporated to dryness by rotary evaporation, and the residue was loaded onto a silica gel column for chromatography.

General procedure III: recycling of the polystyrene-supported Ru catalyst NCPS-Ru

NCPS-Ru **1** recovered from the intramolecular carbenoid C–H insertion reactions was mixed with diazo compound (1.0 mmol) in toluene (2 mL). After completion of the reaction under general procedure II the reaction was centrifuged upon addition of hexane (2 mL), and aliquots were taken from the supernatant for product identification and quantitation by ^1H NMR spectroscopy. The reaction vessel containing the catalyst was recharged with diazo compound and toluene (2 mL) for another consecutive reaction run.

General procedure IV: NCPS-Ru-catalyzed intramolecular carbenoid N–H insertion of diazo compounds

A mixture of diazo compound (1.0 mmol) and NCPS-Ru **1** (1.0 mol %) was stirred in toluene (2 mL) at 70 °C. The reaction was monitored by TLC analysis (20 % EtOAc/hexane) for complete consumption of the diazo starting material. Upon addition of methanol (2 mL) the reaction mixture was centrifuged, and aliquots were taken from the supernatant for product identification and quantitation by ^1H NMR spectroscopy. To obtain pure product, the supernatant was separated and evaporated to dryness by rotary evaporation, and the residue was loaded onto a silica gel column for chromatography.

General procedure V: NCPS-Ru-catalyzed intramolecular cyclopropanation of allyl diazoacetate

A solution of allyl diazoacetate (1.0 mmol) in toluene (2 mL) was added dropwise to a solution of NCPS-Ru **1** (1.0 mol %) in toluene (2 mL) over 10 h at 70 °C. After the addition, stirring was continued until all the diazo compound had been consumed. Upon addition of hexane (2 mL), the reaction mixture was centrifuged, and aliquots were taken from the supernatant for product identification and quantitation by ^1H NMR spectroscopy. To obtain pure product, the supernatant was separated and evaporated to dryness by rotary evaporation, and the residue was loaded onto a silica gel column for chromatography.

General procedure VI: NCPS-Ru-catalyzed intramolecular tandem ammonium ylide/[2,3]-sigmatropic rearrangement reactions

A solution of diazo compound (1.0 mmol) in toluene (2 mL) was added dropwise to a solution of NCPS-Ru **1** (1.0 mol %) in toluene (2 mL) over 2 h at 50 °C. After the addition, stirring was continued until all the diazo compound had been consumed. Upon addition of hexane (2 mL), the reaction mixture was centrifuged, and aliquots were taken from the supernatant for product identification and quantitation by ^{1}H NMR spectroscopy. To obtain pure product, the supernatant was separated and evaporated to dryness by rotary evaporation, and the residue was loaded onto a silica gel column for chromatography.

General procedure VII: NCPS-Ru-catalyzed intermolecular cyclopropanation of alkene with ethyl diazoacetate

A solution of ethyl diazoacetate (1.0 mmol) in toluene (2 mL) was added dropwise to a solution of NCPS-Ru **1** (1.0 mol%) and alkene (2 mmol) in toluene (2 mL) over 10 h at 70 °C. After the addition, stirring was continued until all the diazo compound had been consumed. Upon addition of hexane (2 mL), the reaction mixture was centrifuged, and aliquots were taken from the supernatant for product identification and quantitation by ^{1}H NMR spectroscopy. To obtain pure product, the supernatant was separated and evaporated to dryness by rotary evaporation, and the residue was loaded onto a silica gel column for chromatography.

General procedure VIII: NCPS-Ru-catalyzed intermolecular N−H insertion of amine with ethyl diazoacetate

Ethyl diazoacetate (1.0 mmol) was added in one portion to a mixture of amine (1.1 mmol) and NCPS-Ru **1** (1.0 mol%) in toluene (2 mL) at 70 °C. Upon addition of hexane (2 mL), the reaction mixture was centrifuged, and aliquots were taken from the supernatant for product identification and quantitation by ^{1}H NMR spectroscopy. To obtain pure product, the supernatant was separated and evaporated to dryness by rotary evaporation, and the residue was loaded onto a silica gel column for chromatography.

General procedure IX: NCPS-Ru-catalyzed intermolecular C−H insertion of 1,4-cyclohexadiene with methyl phenyl diazoacetate

A mixture of methyl phenyl diazoacetate (1.0 mmol), 1,4-cyclohexadiene (2.0 mmol), and NCPS-Ru **1** (1.0 mol%) was stirred in toluene (2 mL) at 70 °C for 2 h. Upon addition of hexane (2 mL), the reaction mixture was centrifuged, and aliquots were taken from the supernatant for product identification and quantitation by ^{1}H NMR spectroscopy. To obtain pure product, the supernatant was separated and evaporated to dryness by rotary evaporation, and the residue was loaded onto a silica gel column for chromatography.

General procedure X: NCPS-Ru-catalyzed intermolecular C−H insertion of hydrocarbon with methyl phenyl diazoacetate

A mixture of methyl phenyl diazoacetate and NCPS-Ru **1** (1.0 mol%) was stirred in neat hydrocarbon (2 mL) at 70 °C for 12 h. A Upon addition of hexane (2 mL), the reaction mixture was centrifuged, and aliquots were taken from the supernatant for product identification and quantitation by ^{1}H NMR spectroscopy. To obtain pure product, the supernatant was separated and evaporated to dryness by rotary evaporation, and the residue was loaded onto a silica gel column for chromatography.

Acknowledgements

This work is supported by the Areas of Excellence Scheme (AoE/P10-01) established under the University Grants Committee (HKSAR, China), the Hong Kong Research Grants Council (HKU 7012/05P), HKSAR, and The University of Hong Kong (University Development Fund). We offer our heartfelt thanks to Mr. Frankie Yu-Fee Chan and Mr. Wing-Sang Lee of the Electron Microscope Unit of The University of Hong Kong for their technical assistance. We thank the Materials Characterisation & Preparation Facility (The Hong Kong University of Science & Technology) for technical assistance in recording XPS data.

---

[1] a) M. P. Doyle, M. A. McKervey, T. Ye, *Modern Catalytic Methods for Organic Synthesis with Diazo Compounds*, Wiley, New York, **1998**; b) M. P. Doyle, D. C. Forbes, *Chem. Rev.* **1998**, *98*, 911–936; c) H. M. L. Davies, R. E. J. Beckwith, *Chem. Rev.* **2003**, *103*, 2861–2904; d) V. F. Ferreira, *Curr. Org. Chem.* **2007**, *11*, 177–193; e) H. M. L. Davies, S. J. Hedley, *Chem. Soc. Rev.* **2007**, *36*, 1109–1119.

[2] a) P. M. P. Gois, C. A. M. Afonso, *Eur. J. Org. Chem.* **2004**, 3773–3788; b) H. M. L. Davies, *Angew. Chem.* **2006**, *118*, 6574–6577; *Angew. Chem. Int. Ed.* **2006**, *45*, 6422–6425; c) A. G. H. Wee, *Curr. Org. Synth.* **2006**, *3*, 499–555; d) H. M. L. Davies, J. R. Manning, *Nature* **2008**, *451*, 417–424.

[3] a) M. M. Díaz-Requejo, P. J. Pérez, *J. Organomet. Chem.* **2005**, *690*, 5441–5450; b) M. M. Díaz-Requejo, T. R. Belderrain, M. C. Nicasio, P. J. Pérez, *Dalton Trans.* **2006**, 5559–5566.

[4] a) F. Kakiuchi, N. Chatani in *Ruthenium in Organic Synthesis* (Ed.: S.-I. Murahashi), Wiley-VCH, Weinheim, **2004**, pp. 219–256; b) G. Maas, *Chem. Soc. Rev.* **2004**, *33*, 183–190; c) C.-M. Che, C.-M. Ho, J.-S. Huang, *Coord. Chem. Rev.* **2007**, *251*, 2145–2166.

[5] M. K.-W. Choi, W.-Y. Yu, C.-M. Che, *Org. Lett.* **2005**, *7*, 1081–1084.

[6] J.-L. Zhang, C.-M. Che, *Org. Lett.* **2002**, *4*, 1911–1914.

[7] a) M. P. Doyle, D. J. Timmons, J. S. Tumonis, H.-M. Gau, E. C. Blossey, *Organometallics* **2002**, *21*, 1747–1749; b) M. P. Doyle, M. Yan, H.-M. Gau, E. C. Blossey, *Org. Lett.* **2003**, *5*, 561–563.

[8] a) T. Nagashima, H. M. L. Davies, *Org. Lett.* **2002**, *4*, 1989–1992; b) H. M. L. Davies, A. M. Walji, *Org. Lett.* **2003**, *5*, 479–482; c) H. M. L. Davies, A. M. Walji, T. Nagashima, *J. Am. Chem. Soc.* **2004**, *126*, 4271–4280; d) H. M. L. Davies, A. M. Walji, *Org. Lett.* **2005**, *7*, 2941–2944.

[9] a) J. Lloret, F. Estevan, K. Bieger, C. Villanueva, M. A. Úbeda, *Organometallics* **2007**, *26*, 4145–4151; b) J. Lloret, M. Stern, F. Estevan, M. Sanaú, M. A. Úbeda, *Organometallics* **2008**, *27*, 850–856.

[10] a) J. M. Fraile, J. I. García, J. A. Mayoral, M. Roldán, *Org. Lett.* **2007**, *9*, 731–733; b) J. M. Fraile, J. I. García, J. A. Mayoral, *Coord. Chem. Rev.* **2008**, *252*, 624–646.

[11] a) N. E. Leadbeater, K. A. Scott, L. J. Scott, *J. Org. Chem.* **2000**, *65*, 3231–3232; b) A. Cornejo, J. M. Fraile, J. I. García, M. J. Gil, S. V. Luis, V. Martínez-Merino, J. A. Mayoral, *J. Org. Chem.* **2005**, *70*, 5536–5544; c) A. Cornejo, J. M. Fraile, J. I. García, M. J. Gil, V. Martínez-Merino, J. A. Mayoral, *Tetrahedron* **2005**, *61*, 12107–12110; d) G. Simonneaux, P. L. Maux, Y. Ferrand, J. Rault-Berthelot, *Coord. Chem. Rev.* **2006**, *250*, 2212–2221.

[12] a) M. P. Doyle, M. Y. Eismont, D. E. Bergbreiter, H. N. Gray, *J. Org. Chem.* **1992**, *57*, 6103–6105; b) D. E. Bergbreiter, J. Tian, *Tetrahedron Lett.* **2007**, *48*, 4499–4503; c) M. Glos, O. Reiser, *Org. Lett.* **2000**, *2*, 2045–2048.

[13] For reviews on soluble polymers supports, see: a) D. E. Bergbreiter, *Chem. Rev.* **2002**, *102*, 3345–3384; b) T. J. Dickerson, N. N. Reed, K. D. Janda, *Chem. Rev.* **2002**, *102*, 3325–3344.

[14] S. Kobayashi, R. Akiyama, *Chem. Commun.* **2003**, 449–460.

[15] A previous example of a polymer-supported arene–ruthenium complex: R. Akiyama, S. Kobayashi, *Angew. Chem.* **2002**, *114*, 2714–2716; *Angew. Chem. Int. Ed.* **2002**, *41*, 2602–2604.

[16] D. E. Bergbreiter, C. Li, *Org. Lett.* **2003**, *5*, 2445–2447.

[17] a) D. E. Bergbreiter, P. L. Osburn, T. Smith, C. Li, J. D. Frels, *J. Am. Chem. Soc.* **2003**, *125*, 6254–6260; b) D. E. Bergbreiter, R. Hughes, J. Besinaiz, C. Li, P. L. Osburn, *J. Am. Chem. Soc.* **2003**, *125*, 8244–8249.

[18] J. F. Moulder, W. F. Stickle, P. E. Sobol, K. D. Bomben in *Handbook of X-ray Photoelectron Spectroscopy* (Eds.: J. Chastain, R. C. King), Physical Electronic, Eden Prairie, **1995**.

[19] C. H. Yoon, D. L. Flanigan, B.-D. Chong, K. W. Jung, *J. Org. Chem.* **2002**, *67*, 6582–6584.

[20] Q.-H. Deng, H.-W. Xu, A. W.-H. Yuen, Z.-J. Xu, C.-M. Che, *Org. Lett.* **2008**, *10*, 1529–1532.

[21] C.-Y. Zhou, W.-Y. Yu, P. W. H. Chan, C.-M. Che, *J. Org. Chem.* **2004**, *69*, 7072–7082.

[22] a) T. Ye, M. A. McKervey, *Chem. Rev.* **1994**, *94*, 1091–1160; b) E. Galardon, P. L. Maux, G. Simonneaux, *Tetrahedron* **2000**, *56*, 615–621; c) C. J. Moody, *Angew. Chem.* **2007**, *119*, 9308–9310; *Angew. Chem. Int. Ed.* **2007**, *46*, 9148–9150; d) B. Liu, S.-F. Zhu, W. Zhang, C. Chen, Q.-L. Zhou, *J. Am. Chem. Soc.* **2007**, *129*, 5834–5835.

[23] a) C. Jia, T. Kitamura, Y. Fujiwara, *Acc. Chem. Res.* **2001**, *34*, 633–639; b) V. Ritleng, C. Sirlin, M. Pfeffer, *Chem. Rev.* **2002**, *102*, 1731–1770.

[24] H. M. L. Davies, Q. Jin, P. Ren, A. Y. Kovalenvsky, *J. Org. Chem.* **2002**, *67*, 4165–4169.

[25] For general reviews of polymer-supported catalysts, see: a) N. E. Leadbeater, M. Marco, *Chem. Rev.* **2002**, *102*, 3217–3274; b) C. A. McNamara, M. J. Dixon, M. Bradley, *Chem. Rev.* **2002**, *102*, 3275–3300; c) Q.-H. Fan, Y.-M. Li, A. S. C. Chan, *Chem. Rev.* **2002**, *102*, 3385–3466; d) M. Benaglia, A. Puglisi, F. Cozzi, *Chem. Rev.* **2003**, *103*, 3401–3430; e) B. M. L. Dioos, I. F. J. Vankelecom, P. A. Jacobs, *Adv. Synth. Catal.* **2006**, *348*, 1413–1446; f) M. Heitbaum, F. Glorius, I. Escher, *Angew. Chem.* **2006**, *118*, 4850–4881; *Angew. Chem. Int. Ed.* **2006**, *45*, 4732–4762.

[26] M. M. Shemyakin, Y. A. Ovchinnikov, A. A. Kinyushkin, I. V. Kozhevnikova, *Tetrahedron Lett.* **1965**, *6*, 2323–2327.

[27] Selected examples of NCPS-supported reagents and catalysts: a) T. S. Reger, K. D. Janda, *J. Am. Chem. Soc.* **2000**, *122*, 6929–6934; b) A. B. Charette, M. K. Janes, A. A. Boezio, *J. Org. Chem.* **2001**, *66*, 2178–2180; c) H. S. He, J. J. Yan, R. Shen, S. Zhuo, P. H. Toy, *Synlett* **2006**, 563–566; d) A. Datta, K. Ebert, H. Plenio, *Organometallics* **2003**, *22*, 4685–4691; e) C. K.-W. Kwong, R. Huang, M. Zhang, M. Shi, P. H. Toy, *Chem. Eur. J.* **2007**, *13*, 2369–2376.

[28] J. Chen, G. Yang, H. Zhang, Z. Chen, *React. Funct. Polym.* **2006**, *66*, 1434–1451.

[29] S. Kobayashi, S. Nagayama, *J. Am. Chem. Soc.* **1998**, *120*, 2985–2986.

[30] T. Suzuki, T. Watahiki, T. Oriyama, *Tetrahedron Lett.* **2000**, *41*, 8903–8906.

[31] S. Kobayashi, M. Sugiura, *Adv. Synth. Catal.* **2006**, *348*, 1496–1504.

[32] R. Akiyama, S. Kobayashi, *Angew. Chem.* **2001**, *113*, 3577–3579; *Angew. Chem. Int. Ed.* **2001**, *40*, 3469–3471.

[33] H. Miyamura, R. Matsubara, Y. Miyazaki, S. Kobayashi, *Angew. Chem.* **2007**, *119*, 4229–4232; *Angew. Chem. Int. Ed.* **2007**, *46*, 4151–4154.

[34] J. Yang, J. Y. Lee, T. C. Deivaraj, H.-P. Too, *J. Colloid Interface Sci.* **2004**, *271*, 308–312.

[35] C.-M. Ho, W.-Y. Yu, C.-M. Che, *Angew. Chem.* **2004**, *116*, 3365–3369; *Angew. Chem. Int. Ed.* **2004**, *43*, 3303–3307.

[36] Y. Na, S. Park, S. B. Han, H. Han, S. Ko, S. Chang, *J. Am. Chem. Soc.* **2004**, *126*, 250–258.

[37] B. Therrien, T. R. Ward, M. Pilkington, C. Hoffmann, F. Gilardoni, J. Weber, *Organometallics* **1998**, *17*, 330–337.

Received: March 31, 2008
Revised: May 14, 2008