Organic & Biomolecular Chemistry

PAPER

View Article Online
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Cite this: *Org. Biomol. Chem.*, 2016, **14**, 10988

Bifunctional Ru(II) complex catalysed carbon–carbon bond formation: an eco-friendly hydrogen borrowing strategy†

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Received 13th September 2016,
Accepted 30th October 2016

DOI: 10.1039/c6ob02010k

www.rsc.org/obc

The atom economical borrowing hydrogen methodology enables the use of alcohols as alkylating agents for selective C–C bond formation. A bifunctional 2-(2-pyridyl-2-ol)-1,10-phenanthroline (phenpy-OH) based Ru(II) complex (**2**) was found to be a highly efficient catalyst for the one-pot β-alkylation of secondary alcohols with primary alcohols and double alkylation of cyclopentanol with different primary alcohols. Exploiting the metal–ligand cooperativity in complex **2**, several aromatic, aliphatic and heteroatom substituted alcohols were selectively cross-coupled in high yields using significantly low catalyst loading (0.1 mol%). An outer-sphere mechanism is proposed for this system as exogenous PPh_3 has no significant effect on the rate of the reaction. Notably, this is a rare one-pot strategy for β-alkylation of secondary alcohols using a bifunctional Ru(II)-complex. Moreover, this atom-economical methodology displayed the highest cumulative turn over frequency (TOF) among all the reported transition metal complexes in cross coupling of alcohols.

Introduction

C–C bond forming reactions are one of the most crucial and fundamental reactions in organic chemistry to synthesize functionalized molecules with increasing complexity, rationality and predictability.[1–3] To construct a new C–C bond following the conventional synthetic approach requires toxic, expensive alkyl halides and strong bases which generate stoichiometric amounts of salts as waste.[4,5] This led chemists to develop cleaner and greener methodologies for this chemical transformation. In this regard, substituting alkyl halides with cheap and easy to handle alcohols as electrophiles has a great advantage.[6–8]

Self-coupling of alcohols using strong bases and heterogeneous transition metal catalysts at very high temperature is known for more than a century as the Guerbet reaction.[9] In the last decade, significant efforts have been invested in this field to make this reaction practically viable.[10–15] Several transition metals such as Ir,[16–25] Rh,[26] Pd,[27] Ru,[21,23,24,28–37] Ni,[38] Fe,[39] and Cu[40,41] based complexes were tested for the C–C bond formation *via* alcohol activation following the "borrowing hydrogen" strategy. This methodology mainly consists of three steps: starting with dehydrogenation of alcohols to generate the corresponding carbonyl compounds followed by base catalyzed aldol condensation to afford α,β-unsaturated ketones which are subsequently hydrogenated to afford the longer chain alcohols. This atom economical borrowing hydrogen approach is highly attractive as it provides a wide range of valuable organic molecules with loss of only environmentally friendly water.[42–46]

Catalytic activities of recently reported various complexes in alcohol cross-coupling are listed in Fig. 1. Although noteworthy progress has been made in this field, still the cumulative TOF of these catalysts is significantly low and far from any real-world applicability. From industrial and sustainable chemistry perspective, it is essential to develop a new catalytic system for the efficient synthesis of β-alkylated alcohols with greater selectivity and yield under more environmentally friendly conditions. A carefully designed bifunctional ligand has the potential to craft better performing catalysts to enable the advancement of this reaction.

2-Hydroxypyridine (2-HP) has emerged as an exciting fragment in bifunctional ligand design in both tautomeric forms depending on the reaction conditions (Scheme 2).[47,48] The presence of the pendent –OH group in these metal complexes enhances their catalytic ability. Yamaguchi *et al.* demonstrated dehydrogenation of various alcohols and diols bearing a

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†Electronic supplementary information (ESI) available: General procedures for PPh_3 dependence studies, control experiments procedure, Hg^0 poising experiment, characterization data and NMR spectra of the products. See DOI: 10.1039/c6ob02010k

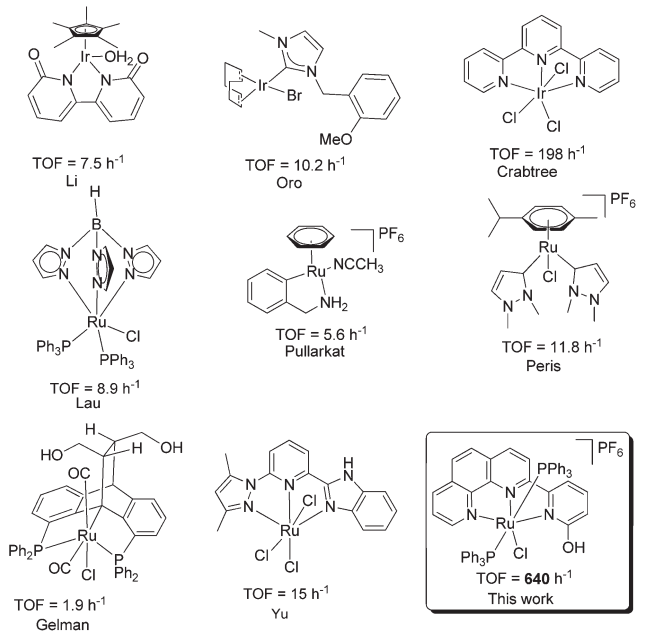
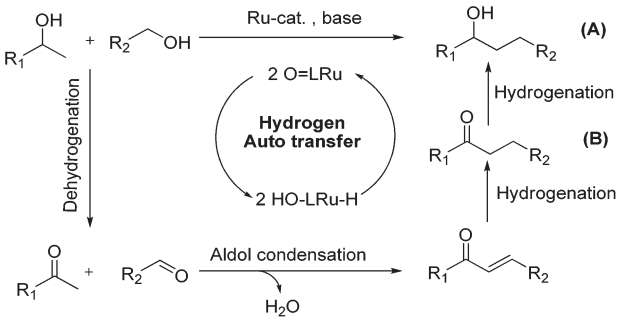
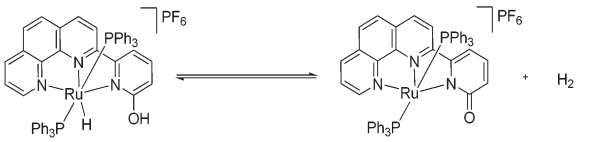


Fig. 1 Cumulative TOF of the reported Ru and Ir catalysts in β-alkylation of alcohols.



Scheme 1 Proposed strategy for β-alkylation of secondary alcohol by using a bifunctional Ru complex.



Scheme 2 Metal–ligand cooperativity in a phenpy-OH based Ru complex (**2**).

bifunctional iridium complex containing a 6,6′-dihydroxy-2,2′-bipyridine ligand.[3,49–51] Recently, Li and co-workers reported bipyridonate iridium catalyzed α-alkylation of ketones using primary alcohols.[18] They also showed β-alkylation of secondary alcohols with primary alcohols in two steps using the same catalysts (TOF = 7.5 h^{-1}).[16] Dehydrogenative cross-coupling of alcohols was also reported by Gelman *et al.* by using bifunctional PC(sp^3)P pincer Ir (TOF = 7.8 h^{-1}) and Ru (TOF = 1.9 h^{-1}) complexes.[24]

We have recently demonstrated that a bifunctional RuCl(phenpy-OH)$(PPh_3)_2PF_6$ (**2**) catalyst was highly effective in transfer hydrogenation of ketones and nitriles.[52] Two 2-HP containing similar Ru(II)-6,6′-dihydroxy terpyridine complexes showed very poor activity in transfer hydrogenation with bulkier ketones as the extra pendent *ortho*-OH may hinder the approach of the substrate to the active site.[53,54] To exhibit the metal–ligand cooperativity only one 2-HP unit is theoretically sufficient. However, all the reported 2-HP-derived catalysts in dehydrogenation of alcohols[2,3,49–51] as well as α-alkylation[16,18] contain at least two 2-HP units.

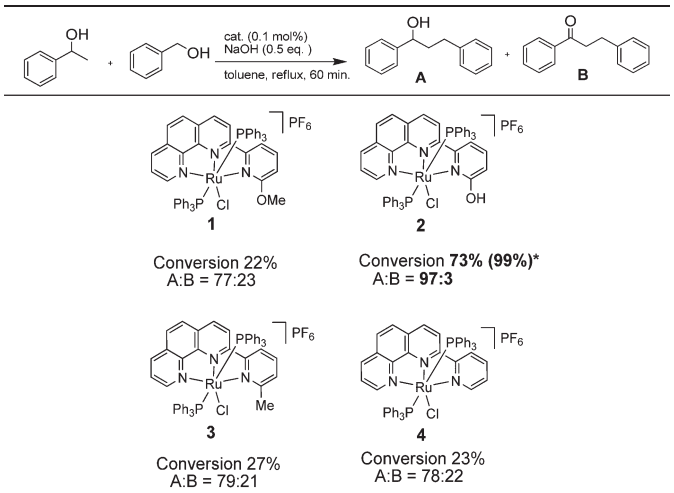
These observations encouraged us to investigate the catalytic properties of this bifunctional ruthenium complex **2** in direct β-alkylation of secondary alcohols with primary alcohols. Fascinated by the high catalytic activity of 2-HP based Ir-complexes in "ligand-promoted dehydrogenation" of alcohols,[2] we envisioned that Ru-complexes bearing a bifunctional tridentate ligand containing one 2-HP unit may facilitate the β-alkylation of secondary alcohols (Scheme 1). However, to the best of our knowledge no such cooperative complex has been reported for the one-pot synthesis of β-alkylated secondary alcohols. Herein, we report a new, highly efficient bifunctional Ru(II) complex catalyzed tandem β-alkylation of secondary alcohols with primary alcohols without any sacrificial hydrogen acceptors.

Results and discussion

In the initial experiment, the reaction of 1-phenylethanol with benzyl alcohol was selected as the benchmark reaction to evaluate the catalytic activities of a series of NNN-pincer Ru(II) complexes for the β-alkylation of secondary alcohols with primary alcohols. The progress of the reaction was monitored by ^{1}H-NMR spectroscopy and the results are shown in Table 1. Complexes **1**, **3** and **4** were found to be moderately active, whereas, complex **2** bearing a bifunctional 2-(2-pyridyl-2-ol)-1,10-phenanthroline (phenpy-OH) ligand exhibited significantly higher activity among all the complexes (Table 1). By using 0.1 mol% of catalyst **2**, 73% conversion of 1-phenylethanol was detected after 1 hour of heating with the highest 1,3-diphenylpropan-1-ol to 1,3-dipheynlpropan-1-one ratio (**A** : **B** = 97 : 3) and within 90 minutes it presented 99% conversion. To the best of our knowledge, the highest reported cumulative TOF value in similar reactions was 198 h^{-1}, which was reported by Crabtree *et al.* using a terpyridine based Ir complex (Fig. 1).[32] To our delight, in comparison to this Ir complex, catalyst **2**/NaOH exhibited much higher activity (TOF = 640 h^{-1}). Notably, using very low catalyst loading (0.002 mol%) this system displayed remarkably high TON (31 500) after 16 h.

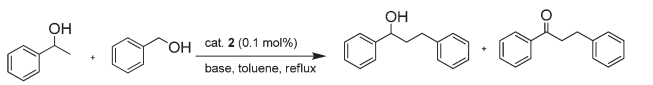
In order to optimize the reaction conditions and to investigate the influence of base and solvent, β-alkylation of 1-phenylethanol with benzyl alcohol was carried out with 0.1 mol% of complex **2** and the results are summarized in Table 2. Conversion of 1-phenylethanol was much higher in toluene

Table 1 β-Alkylation of 1-phenylethanol with benzyl alcohol catalysed by different Ru(II) NNN pincer complexes [a]



[a] Reaction conditions: catalyst (0.1 mol%), 1-phenylethanol (0.654 mmol), benzyl alcohol (0.654 mmol) and NaOH (0.327 mmol) at 125 °C for 60 min (*90 min heating). Conversion and selectivity were determined by ^{1}H NMR based on secondary alcohol.

Table 2 Effect of the base and solvent in the β-alkylation of 1-phenylethanol with benzyl alcohol catalysed by complex **2** [a]



Entry	Base (eq.)	Solvent	Conv.[b] (%)	A/B ratio[c]
1	KO^{t}Bu (0.5)	Toluene	51	92 : 8
2	KOH (0.5)	Toluene	50	87 : 13
3	NaOH (0.5)	Toluene	73	97 : 3
4	NaOH (0.3)	Toluene	52	93 : 7
5	NaOH (1.0)	Toluene	77	97 : 3
6	NaOH (0.5)	Dioxane	13	94 : 6
7	NaO^{i}Pr (0.5)	Toluene	65	90 : 10
8	NaO^{t}Bu (0.5)	Toluene	66	91 : 9
9	Na_2CO_3 (0.5)	Toluene	<1	ND
10	K_2CO_3 (0.5)	Toluene	<1	ND
11	Cs_2CO_3 (0.5)	Toluene	<2	ND
12	No base	Toluene	0	ND
13[d]	NaOH (0.5)	Toluene	0	ND

[a] Reaction conditions: catalyst (0.1 mol%), 1-phenylethanol (0.654 mmol), benzyl alcohol (0.654 mmol) and base (0.327 mmol) at 125 °C for 60 min. [b] Determined by GC analysis based on secondary alcohol. [c] Determined by ^{1}H NMR analysis. [d] No catalyst. ND = Not determined.

than dioxane probably due to the higher boiling point of toluene (Table 2, entry 6). Although complex **2** was not fully soluble in toluene at room temperature; under the reaction conditions in the presence of a base it produced a homogeneous solution which was confirmed by the Hg^0 poisoning test. Among the various bases tested in this reaction, NaOH exhibited the highest efficiency. To determine whether the amount of base influenced the generation of the active catalyst *via* deprotonation of the *ortho*-OH group of the pyridine moiety which affects the reaction rate; we inspected the dependence of the base in the β-alkylation of 1-phenylethanol with benzyl alcohol using complex **2**.[54] Conversion of 1-phenylethanol increased steadily with increasing amounts of NaOH up to 0.5 eq., as can be seen in Fig. 2. However, higher than 0.5 eq. of base did not significantly increase the conversion and saturation behaviour was observed. As expected, no conversion was accomplished without the base or the ruthenium complex (Table 2, entries 12 and 13).

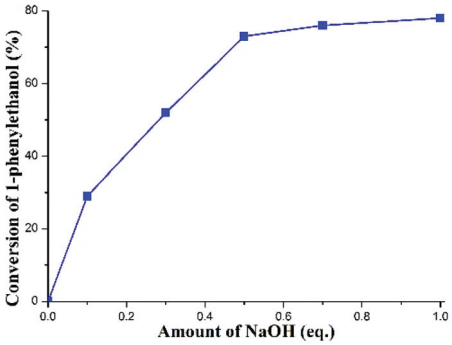
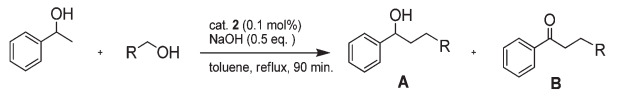


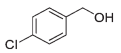
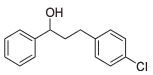
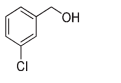
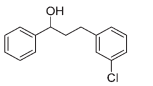
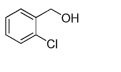
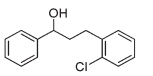
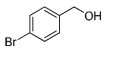
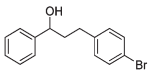
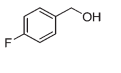
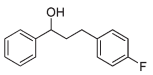
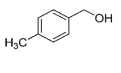
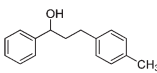
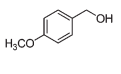
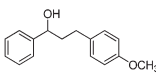
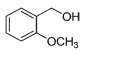
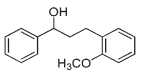
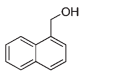
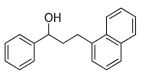
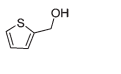
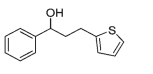
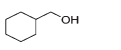
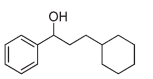
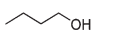
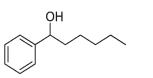
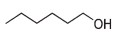
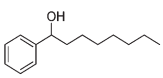
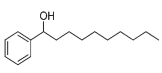
Fig. 2 Dependence of NaOH (with respect to 1-phenylethanol) in β-alkylation of 1-phenylethanol with benzyl alcohol catalysed by complex **2**.

To evaluate the scope of the present catalytic system, β-alkylation of 1-phenylethanol with a variety of primary alcohols was conducted (Table 3). Benzylic alcohols bearing both electron-donating and electron-withdrawing groups at the *para*-position, such as methoxy, methyl, chloro, bromo, and fluoro groups afforded the corresponding long chain β-alkylated secondary alcohols selectively in high yields (Table 3, entries 1 and 4–7). Substrates with electron-donating and electron-withdrawing groups at *ortho*- and *meta*-positions also gave moderate to good yields with high selectivity (Table 3, entries 2, 3 and 8). Furthermore, 1-naphthylmethanol, heteroaromatic substrate 2-thiophenemethanol and cyclohexylmethanol also successfully acted as β-alkylating agents generating the desired products selectively in moderate to good yields (Table 3, entries 9–11). Catalyst **2** showed excellent reactivity in β-alkylation of 1-phenylethanol with more challenging straight chain alcohols, such as 1-butanol, 1-hexanol and 1-octanol (Table 3, entries 12–14). Although the reaction rate was slightly slower compared with benzylic alcohols, interestingly no self-coupling products were detected.[55]

The generality of this catalytic reaction was further expanded by reacting benzyl alcohol with different secondary alcohols (Table 4). 1-Phenylethanol bearing both electron-donating and electron-withdrawing groups at different positions, such as methoxy, methyl, chloro, bromo, and fluoro groups afforded the corresponding β-alkylated alcohols in excellent yields with high selectivity (Table 4, entries 1–8). 1-(Naphthalen-2-yl)ethanol and 1-tetralinol were successfully converted to the coupled alcohol products with high yields (Table 4, entries 9 and 10). The β-alkylation of 1-phenyl-1-

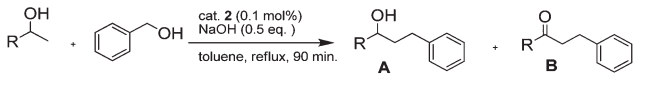
Table 3 Variation of primary alcohols in β-alkylation with 1-phenylethanol[a]

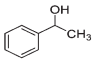
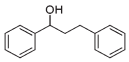
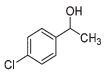
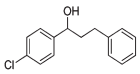
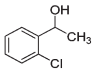
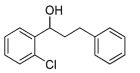
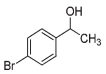
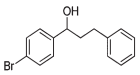
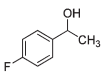
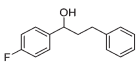


Entry	Primary alcohol	Product	Yield[b]	A/B ratio[b]
1			89	94 : 6
2			96	93 : 7
3			55	99 : 1
4			88	93 : 7
5			90	94 : 6
6			92	92 : 8
7			87	97 : 3
8			65	99 : 1
9			82	93 : 7
10			70	99 : 1
11			68	94 : 6
12[c]			88	87 : 13
13[c]			86	84 : 16
14[c]			81	83 : 17

[a] Reaction conditions: catalyst (0.1 mol%), secondary alcohol (0.654 mmol), benzyl alcohol (0.654 mmol) and NaOH (0.327 mmol) at 125 °C for 90 min. [b] Determined by ^{1}H NMR with respect to secondary alcohol. [c] Heating for 4 hours.

Table 4 Variation of secondary alcohols in β-alkylation with benzyl alcohol[a]



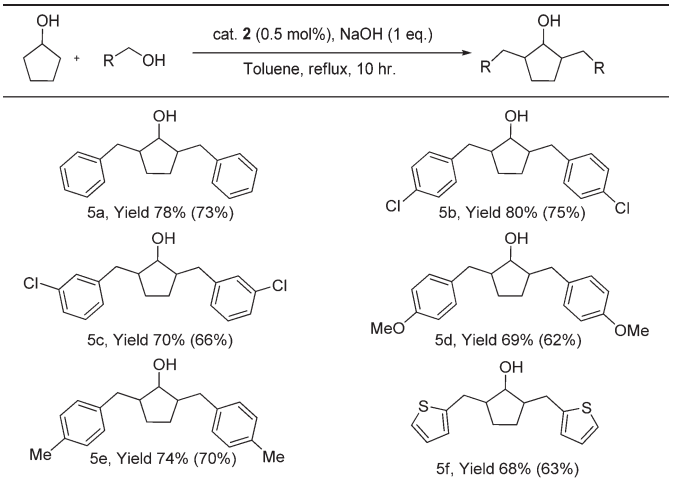
Entry	Secondary alcohol	Product	Yield[b]	A/B ratio[b]
1			99	99 : 1
2			93	94 : 6
3			51	93 : 7
4			92	95 : 5
5			93	93 : 7
6			96	88 : 12
7			91	87 : 13
8			93	92 : 8
9			96	85 : 15
10			95	84 : 16
11			52	99 : 1
12[c]			70	93 : 7
13[c]			72	97 : 3
14[c]			88	93 : 7
15[d]			69	99 : 1

[a] Reaction conditions: catalyst (0.1 mol%), secondary alcohol (0.654 mmol), benzyl alcohol (0.654 mmol) and NaOH (0.327 mmol) at 125 °C for 90 min. [b] Determined by ^{1}H NMR with respect to secondary alcohol. [c] 2 mmol secondary alcohol and 1 mmol benzyl alcohol were used. [d] 0.3 mol% catalyst was used and heated for 5 h.

propanol with benzyl alcohol gave a moderate yield but the selectivity was high (Table 4, entry 11). Aliphatic secondary alcohols, such as 1-cyclopropylethanol, 3-methylbutan-2-ol and 2-heptanol, were also converted to the desired products in good yields, although 2 equiv. of secondary alcohol was required (Table 4, entries 12–14). In addition, heteroaromatic 1-(pyridin-3-yl)ethanol also gave moderate conversion with high selectivity under this catalytic condition (Table 4, entry 15).

To exploit the versatility of this catalytic system, the one-pot double alkylation reaction was tested by treatment of

Table 5 One-pot double alkylation reaction of cyclopentanol using different primary alcohols[a]



[a] Reaction conditions: catalyst (0.5 mol%), cyclopentanol (0.696 mmol), benzyl alcohol (1.46 mmol) and NaOH (0.696 mmol) at 125 °C for 10 h. Yield determined by ^{1}H NMR with respect to primary alcohol (isolated yields are given in parenthesis).

cyclopentanol with various primary alcohols in the presence of complex **2**. To our delight, this catalytic system afforded the desired double alkylated secondary alcohol products in moderate to good yields (Table 5). The electron withdrawing group at the *para* position increased the yield of this reaction (Table 5, **5b**) whereas the reverse was true for the electron donating group (Table 5, **5d** and **5e**). Heteroaromatic 2-thiophenemethanol was also successfully utilized as a double alkylating agent which showed a moderate yield (Table 5, **5f**).

Reaction mechanism

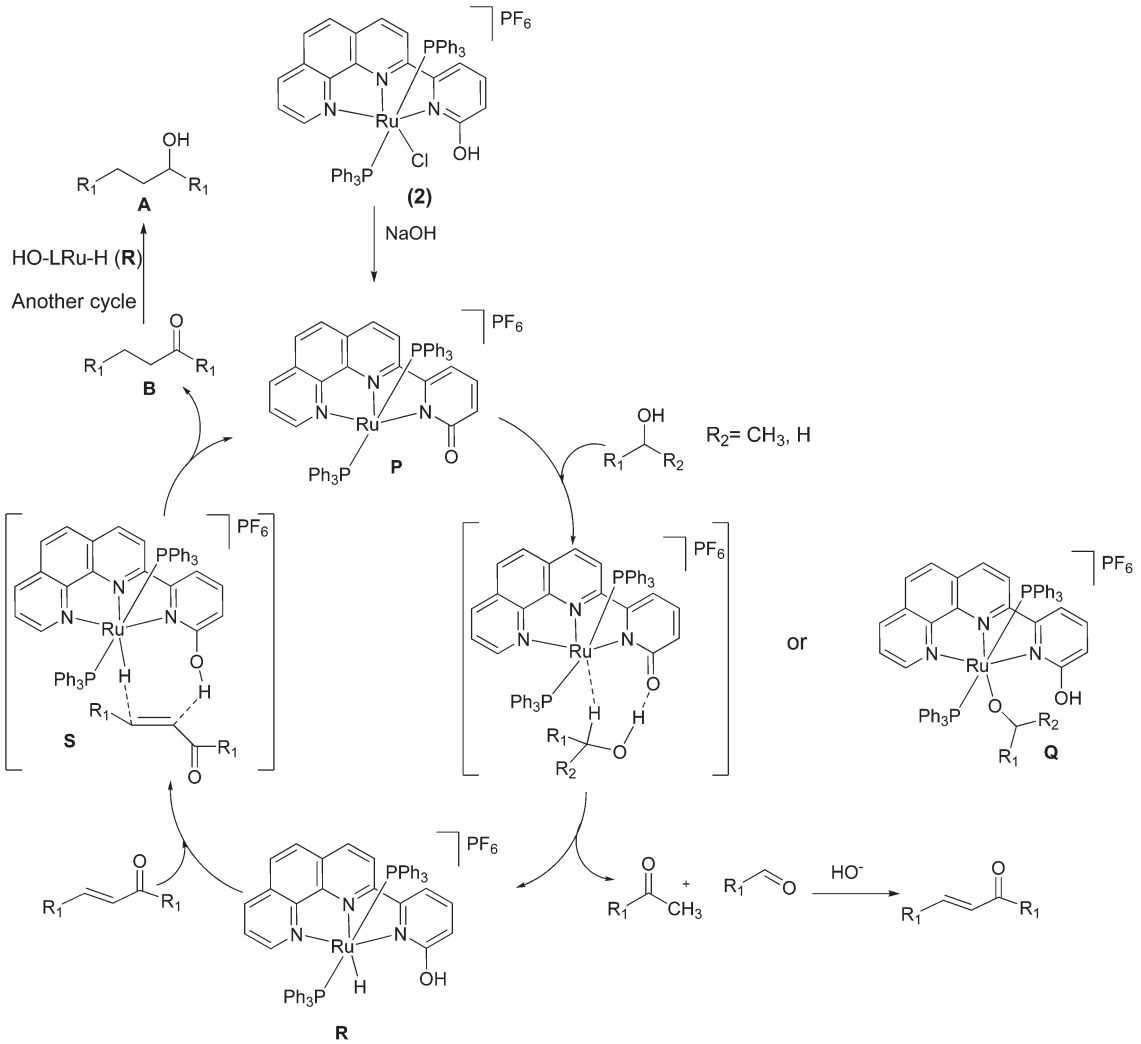
Based on the bifunctional nature of the catalyst **2** and related literature reports,[2,3,16,18,54] we proposed a probable mechanism for the β-alkylation of secondary alcohols with primary alcohols as shown in Scheme 3. In the initial step, in the presence of a base complex **2** is converted to a Ru(II)–bipyridonate complex (**P**) and addition of alcohol following a concerted outer-sphere pathway would generate the ruthenium hydride species (**R**) and the corresponding carbonyl compound. This outer-sphere pathway is more favoured over the inner-sphere mechanism as indicated by many recent reports.[56–59] However, addition of alcohol to **P** followed by β-hydrogen elimination to afford **R** cannot be completely ruled out. Next, base-mediated cross-aldol condensation between the resulting aldehydes and ketones produces the α,β-unsaturated ketones. Finally, metal–ligand cooperativity enables the hydrogenation of the double bond of the α,β-unsaturated ketone by simultaneous transfer of a hydroxyl proton from the ligand and the hydride on the ruthenium centre to produce the ketone (**B**), which then further reduces to alcohol (**A**) following a similar outer-sphere mechanism.

To confirm the possible steps in this proposed mechanism several control experiments were carried out. The reaction of 1-phenylethanol with benzaldehyde in the presence of complex **2** under optimum catalytic conditions provided a mixture of products comprising 72% of 1,3-diphenylpropan-1-one (**B**), 11% of 1,3-diphenylpropan-1-ol (**A**), and 17% of 1,3-diphenylpropen-1-one (chalcone) (91% conversion of 1-phenylethanol based on ^{1}H NMR analysis) (Scheme 4, eqn (1)). Similar results were observed when the reverse reaction, *i.e.* the reaction of acetophenone with benzyl alcohol was performed (Scheme 4, eqn (2)). In this case, the product distribution was 75% of **B**, 9% of **A** and 16% of chalcone (93% conversion of 1-phenylethanol based on ^{1}H NMR analysis). In both of these control experiments among the product mixtures, saturated ketone 1,3-diphenylpropan-1-one (**B**) was identified as the major and 1,3-diphenylpropen-1-one (**C**, chalcone) as the minor product which clearly indicates that the transfer of hydrogen from starting alcohols to the unsaturated aldol condensation product (**C**) happened smoothly. The absence of 1,3-diphenylprop-2-en-1-ol (only ketone hydrogenated product) indicates that the reduction of the C=C bond of the α,β-unsaturated ketone was much faster than the reduction of the C=O bond under catalytic conditions.[39]

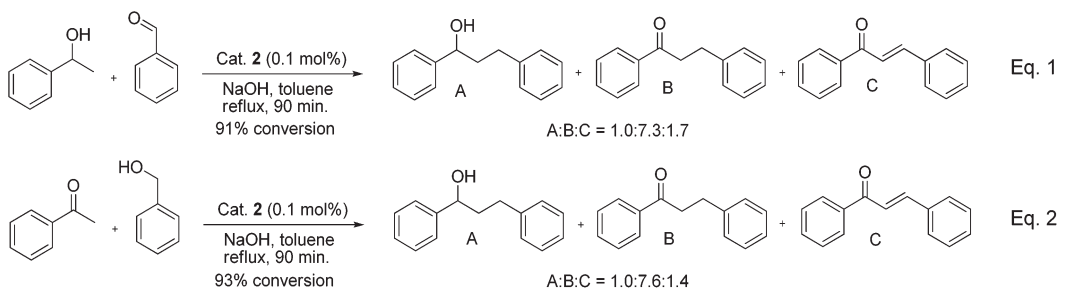
To obtain more information regarding the hydrogenation mechanism of the α,β-unsaturated ketones, two control experiments with chalcone were executed. The transfer hydrogenation of chalcone in the presence of 1-phenylethanol afforded exclusively **B** in 87% yield (Scheme 5, eqn (3)). Under similar conditions, the reaction of benzyl alcohol with chalcone produced 76% of **B** and 3% of **A** (Scheme 5, eqn (4)). These results further suggest that complex **2** can effectively catalyze the transfer of hydrogen from the starting alcohols to the C=C bond of chalcone and the reduction of the C=C bond is preferred over the C=O bond.[24,60,61]

To inspect if the Ru metal center was involved in the cross-aldol condensation step, a reaction of acetophenone and benzaldehyde was performed in the presence and absence of complex **2** using the optimum catalytic conditions. In the presence of complex **2**, 1-phenylethanol was quantitatively converted to chalcone (**C**) within 90 minutes (Scheme 6, eqn (5)). However, in the absence of **2**, only 74% conversion of 1-phenylethanol was observed (Scheme 6, eqn (6)). In this reaction a small amount of benzoic acid and benzyl alcohol was generated from the base induced Cannizzaro reaction of benzaldehyde and trace amounts of 1,3-diphenylbut-2-en-1-one were also produced from self-condensation of acetophenone. Results from these experiments may indicate the involvement of the ruthenium catalyst in the cross-aldol condensation reaction. With the NHC-Ir complex a similar result was also reported by Oro *et al.*[62]

In order to probe the selectivity in β-alkylation of secondary alcohols with primary alcohols, we studied the time dependent product distribution of this catalytic reaction. As reported in Fig. 3, the concentrations of 1-phenylethanol and benzyl alcohol gradually decreased and concurrently, the concentration of 1,3-diphenylpropan-1-ol (**A**) increased. During the



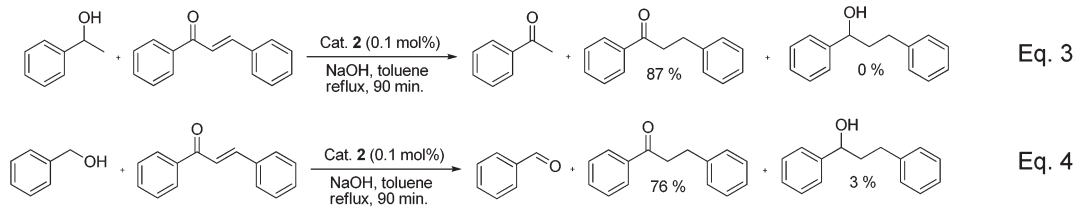
Scheme 3 Proposed mechanism for β-alkylation of secondary alcohol with primary alcohol catalysed by complex **2**.



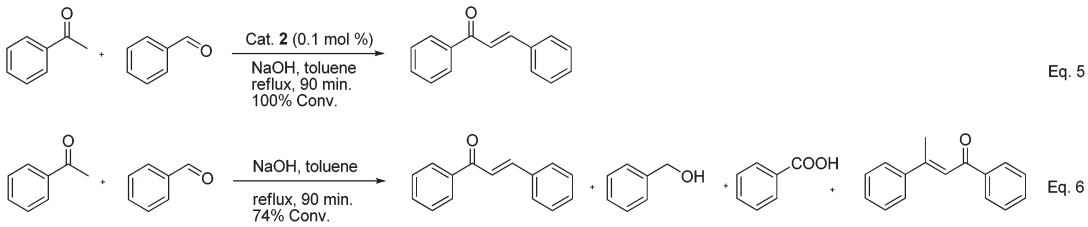
Scheme 4 Control experiments for mechanistic studies of β-alkylation of alcohols.

whole course of the reaction, the concentration of 1,3-diphenylpropan-1-one (**B**) was minimal and also did not change significantly. On the other hand, we never detected a trace amount of the cross-aldol product. This result advocated that with increasing reaction time the selectivity of alcohol (**A**) increases; whereas throughout the process the concentration of keto (**B**) remains the same.[62]

In the hydrogenation reaction excess of PPh_3 significantly reduces the reaction rate for a catalytic system following the inner-sphere mechanism as ligand dissociation is considered as an initiation step.[63–68] In contrast, an excess of PPh_3 has no significant effect on the catalytic activity of a system following the outer-sphere mechanism.[69] In order to inspect which mechanism our system was following, β-alkylation of 1-phenyl-



Scheme 5 Transfer hydrogenation of chalcone using 1 equiv. of alcohol.



Scheme 6 Cross aldol condensation in the presence and absence of cat. **2**.

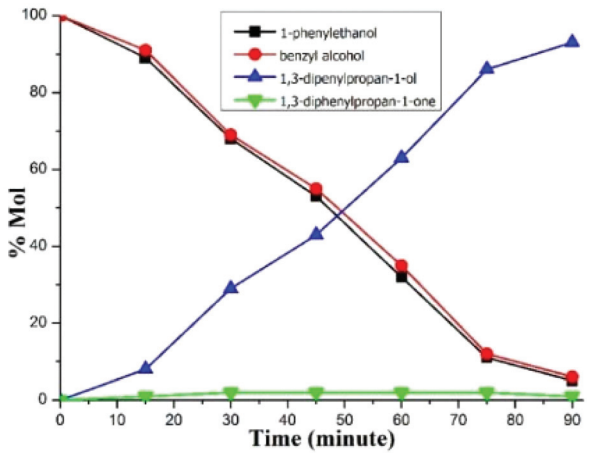


Fig. 3 Time dependent product distribution in β-alkylation of 1-phenylethanol with benzyl alcohol catalysed by complex **2**.

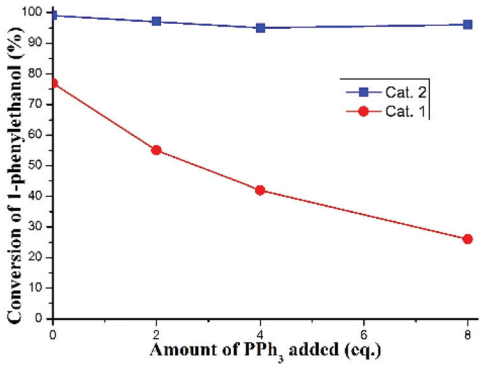


Fig. 4 Effect of externally added PPh_3 (with respect to cat.) on cat. **1** and cat. **2** in β-alkylation of 1-phenylethanol with benzyl alcohol. Conditions: 0.1 mmol% cat., 1-phenylethanol (0.654 mmol), benzyl alcohol (0.654 mmol), NaOH (0.327 mmol), toluene, 125 °C. Time for cat. **1** (180 min) and Cat **2** (90 min).

ethanol with benzyl alcohol was carried out using both the complexes **1** and **2** in the presence of excess of PPh_3 (2–8 eq.). The rate of β-alkylation of secondary alcohol was significantly affected when excess of PPh_3 was added to the reaction mixture containing complex **1** (Fig. 4). After 3 h, in the absence of additional PPh_3 conversion of 1-phenylethanol was 77% with complex **1**. But, under similar reaction conditions with 8 eq. of PPh_3 conversion of 1-phenylethanol was decreased drastically to 28%. However, with catalyst **2** exogenous PPh_3 had no significant effect (Fig. 4). This result clearly validates that in the rate determined step, dissociation of PPh_3 did not occur with the **2**/NaOH system and probably it was following an outer-sphere mechanism.

Conclusion

A ruthenium(II) complex bearing a bifunctional phenpy-OH ligand was found to be a highly efficient catalyst for the atom economical β-alkylation of secondary alcohols with primary alcohols. This work demonstrates a new, practical and greener methodology to construct C–C bonds using readily available, less toxic alcohols and produces only H_2O as a byproduct. The metal–ligand cooperativity in complex **2** accounts for the remarkably high catalytic activity in coupling of a variety of secondary alcohols with numerous primary alcohols to yield the corresponding β-alkylated alcohols with high selectivity. Notably, double alkylation of cyclopentanol with various primary alcohols also proceeded smoothly. Control experiments indicated the involvement of the ruthenium catalyst in cross-aldol condensation and that hydrogenation of the C=C bond of the α,β-unsaturated ketone was much faster than the hydrogenation of the ketone with this system. Mechanistic studies with excess of PPh_3 in β-alkylation of 1-phenylethanol with benzyl alcohol revealed that the **2**/NaOH system was

following an outer-sphere mechanism. To the best of our knowledge, this present protocol is a rare one-pot atom economical synthetic strategy for β-alkylation of secondary alcohols with primary alcohols using a bifunctional Ru(II)-complex which exhibited the highest reactivity among all the reported catalysts.

Experimental section

General procedures and materials

All reactions were carried out under an inert atmosphere using standard Schlenk-line techniques. Glassware was flame-dried under vacuum prior to use. Solvents were dried according to literature methods, distilled under argon and deoxygenated prior to use. $RuCl_3{\cdot}nH_2O$ (39% Ru) and $PdCl_2$ (60% Pd) were purchased from Arora Matthey, India. 2-Bromo phenanthroline, 5-methoxy-2-(tributylstannyl)pyridine, 5-methyl-2-(tributylstannyl)pyridine, and 2-(tributylstannyl)pyridine were synthesized following the literature procedures.[70–74] Syntheses of complexes **1** and **2** were already reported from our group.[52] All the chemicals were purchased from Sigma-Aldrich, Alfa Aesar, SDFCL and Spectrochem. ^1H, ^{13}C, ^{31}P NMR spectra were recorded on JEOL 400 and 500 MHz spectrometers. Elemental analyses were performed on a Thermoquest EA1110 CHNS/O analyser. The crystallized compounds were powdered, washed several times with dry diethyl ether and dried under vacuum for at least 48 h prior to elemental analyses. ESI-MS was performed using a Waters Micromass Quattro Micro triple-quadrupole mass spectrometer. All the GC analysis was done using a Perkein Elmer Clarus 600 Gas Chromatograph and GC-MS was performed using an Agilent 7890 A Gas Chromatograph equipped with an Agilent 5890 triple-quadrupole mass system.

Synthesis of 2-(6-methylpyridin-2-yl)-1,10-phenanthroline

A mixture of 2-bromo phenanthroline (0.772 mmol, 0.20 g), 5-methyl-2-tributhylstannylpyridine (1.544 mmol, 0.589 g) and $Pd(PPh_3)_4$ (0.077 mmol, 0.089 g) in 30 mL of toluene was heated at the reflux temperature for 4 days. The mixture was allowed to cool to room temperature and the solvent was removed in a vacuum. The final product was purified by column chromatography (using neutral alumina) with hexane–ethyl acetate as the eluent. A light yellow product was obtained (0.170 g, 81%). ^1H NMR (400 MHz, $CDCl_3$): δ = 9.21 (dd, $J_{H,H}$ = 4.12 Hz, $J_{H,H}$ = 2.28 Hz, 1H), 8.79 (d, $J_{H,H}$ = 8.24 Hz, 1H), 8.72 (d, $J_{H,H}$ = 7.76 Hz, 1H), 8.33 (d, $J_{H,H}$ = 8.24 Hz, 1H), 8.24 (dd, $J_{H,H}$ = 8.02 Hz, $J_{H,H}$ = 6.40 Hz, 1H), 7.82–7.75 (m, 3H), 7.63 (dd, $J_{H,H}$ = 8.24 Hz, $J_{H,H}$ = 3.64 Hz, 1H), 7.21 (d, $J_{H,H}$ = 7.32 Hz, 1H), 2.67 (s, 3H). $^{13}C\{^1H\}$ NMR (500 MHz, $CDCl_3$): 157.9, 156.6, 155.5, 150.4, 146.4, 145.4, 137.2, 136.9, 136.2, 129.1, 128.7, 126.6, 123.8, 122.9, 121.0, 119.8, 24.7. ESI-MS: m/z = 273.1182 (100%, MH^+).

Synthesis of 2-(pyridin-2-yl)-1,10-phenanthroline

A mixture of 2-bromo phenanthroline (0.772 mmol, 0.2 g), 2-tributhylstannylpyridine (1.543 mmol, 0.568 g) and $Pd(PPh_3)_4$ (0.077 mmol, 0.089 g) in 30 mL of toluene was heated at the reflux temperature for 3 days. The mixture was allowed to cool to room temperature and the solvent was removed in a vacuum. The final product was purified by column chromatography (using neutral alumina) with hexane–ethyl acetate as the eluent. A cream white product was obtained (0.163 g, 82%). ^1H NMR (400 MHz, $CDCl_3$): δ = 9.22 (dd, $J_{H,H}$ = 4.58 Hz, $J_{H,H}$ = 3.08 Hz, 1H), 8.98 (d, $J_{H,H}$ = 7.96 Hz, 1H), 8.79 (d, $J_{H,H}$ = 8.56 Hz, 1H), 8.72 (d, $J_{H,H}$ = 4.92 Hz, 1H), 8.36 (d, $J_{H,H}$ = 8.56 Hz, 1H), 8.26 (dd, $J_{H,H}$ = 8.24 Hz, $J_{H,H}$ = 6.72 Hz, 1H), 7.90 (dt, $J_{H,H}$ = 7.94 Hz, $J_{H,H}$ = 1.84 Hz, 1H), 7.78 (d, $J_{H,H}$ = 8.56 Hz, 1H), 7.64 (dd, $J_{H,H}$ = 7.94 Hz, $J_{H,H}$ = 3.68 Hz, 1H), 7.36 (dt, $J_{H,H}$ = 5.04 Hz, $J_{H,H}$ = 1.24 Hz, 1H). $^{13}C\{^1H\}$ NMR (500 MHz, $CDCl_3$), δ = 156.2, 156.1, 150.4, 149.1, 146.3, 145.7, 137.1, 137.0, 136.3, 129.1, 128.8, 126.8, 126.6, 124.2, 123.0, 122.8, 120.9. ESI-MS: m/z = 258.1030 (100%, MH^+).

Synthesis of *trans*-RuCl(phenpyMe)$(PPh_3)_2PF_6$ (3)

In a Schlenk flask 2-(6-methylpyridin-2-yl)-1,10-phenanthroline (0.020 g; 0.074 mmol) and $RuCl_2(PPh_3)_3$ (0.071 g; 0.074 mmol) were taken and 40 mL dry methanol was added. The mixture was refluxed for 24 hours under an argon atmosphere. It was allowed to cool to room temperature and solid ammonium hexafluorophosphate (0.240 g; 1.474 mmol) was added to the solution. The solution was stirred at room temperature overnight, during which a red precipitate emerged. The precipitate was filtered, washed with dry diethyl ether and hexane and dried under vacuum to provide the title compound as a brick red powder (0.041 g; 70%). ^1H NMR (500 MHz, CD_2Cl_2), δ = 9.23 (d, $J_{H,H}$ = 5.2 Hz, 1H), 8.35 (d, $J_{H,H}$ = 8.19 Hz, 1H), 8.26 (d, $J_{H,H}$ = 8.75 Hz, 1H), 8.15 (d, $J_{H,H}$ = 8.75 Hz, 1H), 7.98 (d, $J_{H,H}$ = 7.55 Hz, 1H), 7.94 (bs, 2H), 7.86–7.77 (m, 2H), 7.45 (d, $J_{H,H}$ = 7.6 Hz, 1H), 7.35 (t, $J_{H,H}$ = 4.3 Hz, 6H), 7.28–7.15 (m, 12H), 6.92–6.65 (m, 12H), 2.68 (s, 3H). $^{13}C\{^1H\}$ NMR (125 MHz, CD_2Cl_2): δ = 157.72, 137.10, 135.36, 134.54, 134.15, 132.89, 132.72, 130.46, 130.42, 130.11, 129.11, 129.64, 128.82, 128.69, 128.21, 127.91, 127.86, 126.91, 125.26, 121.46, 120.84, 116.33, 28.21. $^{31}P\{^1H\}$ NMR, (202 MHz, CD_2Cl_2), δ = 17.90 (s, PPh_3), −145.06 (sep., J = 703.6, PF_6^-). ESI-MS: m/z = 932.1780 ($[M-PF_6]^+$). Anal. Calculated ($C_{54}H_{43}ClF_6N_3P_3Ru$) (found): C, 60.20 (59.85); H, 4.02 (3.81); N, 3.90 (3.62).

Synthesis of *trans*-RuCl(phenpy)$(PPh_3)_2PF_6$ (4)

In a Schlenk flask 2-(pyridin-2-yl)-1,10-phenanthroline (0.020 g; 0.077 mmol) and $RuCl_2(PPh_3)_3$ (0.075 g; 0.077 mmol) were taken and 40 mL dry methanol was added. The mixture was refluxed for 24 hours under an argon atmosphere. It was allowed to cool to room temperature and solid ammonium hexafluorophosphate (0.253 g; 1.554 mmol) was added to the solution. The solution was stirred at room temperature overnight, during which a red precipitate emerged. The precipitate was filtered, washed with dry diethyl ether and hexane and dried under vacuum to provide the title compound as a crimson red powder. Yield: (0.037 g; 74%). ^1H NMR (500 MHz, CD_2Cl_2): δ = 9.46 (d, $J_{H,H}$ = 4.60 Hz, 1H), 9.12 (d, $J_{H,H}$ = 5.00 Hz, 1H), 8.17 (d, $J_{H,H}$ = 8.05 Hz, 1H), 7.90 (d, $J_{H,H}$ = 8.00 Hz, 1H),

7.79–7.69 (m, 4H), 7.56–7.50 (m, 2H), 7.19 (t, $J_{H,H}$ = 5.9 Hz, 1H), 7.13 (t, $J_{H,H}$ = 7.30 Hz, 6H), 7.55–7.59 (m, 2H), 7.14 (t, $J_{H,H}$ = 7.2 Hz, 6H), 6.93 (t, $J_{H,H}$ = 7.6 Hz 12H), 6.82–6.86 (m, 12H), 7.07–7.04 (m, 12H), 6.96 (t, $J_{H,H}$ = 7.55 Hz, 12H). $^{13}C\{^1H\}$ NMR (100 MHz, CD_2Cl_2): δ = 157.75, 156.99, 156.70, 156.10, 147.76, 136.72, 135.01, 132.58, 129.90, 129.52, 129.36, 129.20, 129.07, 128.35, 128.05, 127.98, 126.99, 126.93, 125.40, 122.68, 120.93. $^{31}P\{^1H\}$ NMR, 202 MHz (CD_2Cl_2), δ (ppm): 19.45 (s, PPh_3), −145.08 (sep., J = 704.4, PF_6^-). ESI-MS: m/z = 918.1582 ($[M-PF_6]^+$). Anal. Calculated ($C_{53}H_{41}ClF_6N_3P_3Ru$) (found): C, 59.86 (59.57); H, 3.89 (3.73); N, 3.95 (3.57).

General procedure for the catalytic β-alkylation of alcohols

The catalyst solution was prepared by dissolving complex **2** in CH_3CN (1 mL) in an argon filled glovebox. Then the red catalyst solution (0.1 mol%) was taken into a Schlenk tube and the solvent was removed under vacuum. After that secondary alcohol (0.654 mmol), primary alcohol (0.654 mmol), NaOH (0.327 mmol) and 3.0 ml toluene were added under an argon atmosphere. Then, the tube was dipped in an oil bath (the red color immediately changed to purple) and heated for 90 minutes at 125 °C (oil bath temperature). It was cooled to room temperature and 10 μL solution was syringed out for GC analysis (faint purple color). The reaction mixture was concentrated under reduced pressure and submitted crude for NMR to calculate the conversion and product selectivity. The final desired alcohol (**A**, major) and ketone (**B**, minor) products were isolated and purified by column chromatography (silica) using hexane–ethyl acetate as the eluent.

General procedure for the catalytic double β-alkylation of cyclopentanol

The catalyst solution was prepared by dissolving complex **2** in CH_3CN (1 mL) in an argon filled glovebox. Then the red catalyst solution (0.5 mol%) was taken into a Schlenk tube and the solvent was removed under vacuum. After that cyclopentanol (0.696 mmol), primary alcohol (1.46 mmol), NaOH (0.696 mmol) and 3.0 mL toluene were added under an argon atmosphere. Then, the tube was dipped in an oil bath (the red color immediately changed to purple) and heated for 10 hours at 125 °C (oil bath temperature). It was cooled to room temperature (faint purple color), concentrated under reduced pressure and submitted crude for NMR to calculate the conversion. The final desired products were isolated and purified by column chromatography (silica) using hexane–ethyl acetate as the eluent.

Conflict of interest

The authors declare no competing financial interests.

Acknowledgements

We are grateful to DST-INSPIRE, Science and Engineering Research Board India and Indian Institute of Technology Kanpur for financial support. K. C. and B. P. thank UGC India and M. M., B. C. R. and S. S. thank CSIR India, for fellowships.

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