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Graphical Abstract

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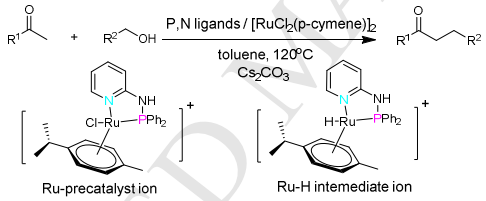

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Efficient alkylation of ketones with primary alcohols catalyzed by ruthenium(II)/P,N ligand complexes

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ABSTRACT

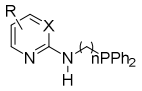
An efficient catalytic system containing $[RuCl_2(\eta^6\text{-p-cymene})]_2$ and one P,N ligand, N-diphenylphosphino-2-aminopyridine (**L1**) was loaded in catalyzing the alkylation of ketones with primary alcohols for a diverse array of substrates. Other five P,N ligands based on pyridin-2-amine and pyrimidin-2-amine were also examined in this reaction to explore the influence of steric hindrance and electronic effects. Monitoring by ^{1}H NMR and ESI-MS reveals a stable cationic **L1**-coordinated ruthenium hydride intermediate, identified as $[Ru(\eta^6\text{-p-cymene})(\kappa^2\text{-}\mathbf{L1})H]^+$. Organic intermediates consistent with a three-step dehydrogenation, alkylation and hydrogenation pathway were also observed. The final step in this reaction, the ruthenium-catalysed transfer hydrogenation reduction of α,β-unsaturated ketone with benzyl alcohol was performed separately.

1. Introduction

Alkylation of ketones with alcohols is an atom efficient, C-C bond forming transformation. Traditionally, this synthetic outcome has been achieved by the coupling of an alkyl halide with an enolate. Such a nucleophilic substitution generates a stoichiometric equivalent of salt as waste.[1-2] Adopting the 'borrowing hydrogen' (BH)[3] strategy for the alkylation of ketones with alcohols has recently attracted considerable attention and has been achieved using Ru,[4] Ir,[5] Pd,[6] and other transition-metal[7] catalysts. These noble metal ions generally require phosphines,[4e,j,5g] N-heterocyclic carbenes[6c] and N-donor ligands[4d] to stabilize the active species with low oxidation states. Whereas some limitations involving needing the addition of hydrogen acceptors, unsatisfactory yield or a high temperature were observed. P,N ligand-stabilized transition metal catalysts have already exhibited excellent performance in some coupling reactions based on BH strategy.[8] Recently, Kempe and coworkers[8d-h] developed several Ir-P,N ligand systems for the alkylation of amine derivatives. Similarly Kirchner's group[9] synthesized a series of cationic half-sandwich Ru(II) complexes, among which $[Ru(\eta^6\text{-p-cymene})(\kappa^2\text{(P,N)-PN})Cl]Cl$ (PN = N-diphenylphosphino-2-aminopyridine) was shown to efficiently catalyze the transfer hydrogenation reduction of acetophenone to 1-phenyl ethanol. However, few researchers have applied these ligands to the α-alkylation of ketones up to date. Ruthenium is significantly less expensive than iridium[5e,f] and thus we have investigated the combination of P,N ligands with ruthenium to accomplish the alkylation of ketones with primary alcohols.

Ruthenium hydride complexes are well-known, versatile catalysts or intermediates in a variety of organic transformations.[4d,e,10] Although some Ru-H complexes could be obtained from commercially sources and used as catalysts for organic syntheses, the reports of the Ru-H intermediates identified in BH-strategy alkylation are still rare. Very recently, Ru-hydride intermediates have been shown to possess potent anticancer and antioxidant activity by virtue of a transfer hydrogenation mechanism of action.[11,12] In these examples, it is presumed that a ruthenium-hydride intermediate might be the hydrogen carrier. Identifying such an intermediate would be used for the confirmation of the mechanism of the reaction and would provide the valuable information for the design of new catalytic systems.

Herein, we report the alkylation of ketones with alcohols through the combination of one dimeric complex $[RuCl_2(\eta^6\text{-p-cymene})]_2$ and one P,N ligand, N-diphenylphosphino-2-aminopyridine (**L1**). Other five P,N ligands (**L2**-**L6**) based on pyridin-2-amine and pyrimidin-2-amine (Fig. 1) were also prepared to systematically study the influence of steric and electronic effects. Most notably, a persistent ruthenium hydride intermediate $[Ru(\eta^6\text{-p-cymene})(\kappa^2\text{-}\mathbf{L1})H]^+$ in this catalytic system was identified by *in situ* monitoring the reaction using ^{1}H NMR and ESI-MS techniques.



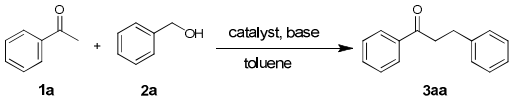
L1 n=0, R=H, x=CH
L2 n=1, R=H, x=CH
L3 n=0, R=H, x=N
L4 n=0, R=4-OCH_3, x=CH
L5 n=0, R=4-Cl, x=CH
L6 n=0, R=6-CH_3, x=CH

Fig. 1. Conformation of P,N ligands **L1-L6**.

2. Results and discussion

We first examined the alkylation of acetophenone (**1a**) with benzyl alcohol (**2a**) as a model reaction. Three Ru sources, six P,N ligands, and five diphosphine ligands were compared (Table 1). Among the three Ru sources, $[RuCl_2(\eta^6\text{-p-cymene})]_2$ showed better activity toward such alkylation reaction than $RuCl_3$ and $RuCl_2(PPh_3)_3$ (Table 1, entries 1-3). Xantphos and dppm appeared to slow the reaction slightly (Table 1, entries 4-5) while more flexible diphosphine ligands improved the product yield slightly (Table 1, entries 6-8). All P,N ligands gave equivalent or improved yields relative to those obtained in the ligand-free reaction, with pyrimidine **L3** (Table 1, entry 11) and the more hindered pyridine **L6** (entry 14) at the low end of the yield range. In the cases of **L1** and **L2** (Table 1, entries 9 and 10), the yields of **3aa** were higher than those of the diphosphines (Table 1, entries 5-8), which may be attributed to the less steric hindrance of the pyridyl groups. This trend is similar to that reported previously.[13] Electron donating or withdrawing groups on the pyridine moiety exert no impact on the product yield (Table 1, entries 9 and 12-13). Considering the good performance and relatively low cost of **L1**, we chose this ligand for subsequent experiments.

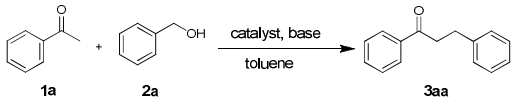
Table 1. The effects of different Ru sources and ligands on the alkylation of **1a** with **2a**.[a]



Entry	Ru-catalyst	Yield (%)
1	$RuCl_3$	16
2	$RuCl_2(PPh_3)_3$	63
3	$[RuCl_2(\eta^6\text{-p-cymene})]_2$	74
4	$[RuCl_2(\eta^6\text{-p-cymene})]_2$/Xantphos	63
5	$[RuCl_2(\eta^6\text{-p-cymene})]_2$/dppm	72
6	$[RuCl_2(\eta^6\text{-p-cymene})]_2$/dppe	79
7	$[RuCl_2(\eta^6\text{-p-cymene})]_2$/dppp	84
8	$[RuCl_2(\eta^6\text{-p-cymene})]_2$/dppb	83
9	$[RuCl_2(\eta^6\text{-p-cymene})]_2$/**L1**	87
10	$[RuCl_2(\eta^6\text{-p-cymene})]_2$/**L2**	85
11	$[RuCl_2(\eta^6\text{-p-cymene})]_2$/**L3**	74
12	$[RuCl_2(\eta^6\text{-p-cymene})]_2$/**L4**	87
13	$[RuCl_2(\eta^6\text{-p-cymene})]_2$/**L5**	87
14	$[RuCl_2(\eta^6\text{-p-cymene})]_2$/**L6**	78

[a] Reaction conditions: **1a** (1 mmol), **2a** (1.1 mmol), Cs_2CO_3 (0.6 mmol), catalyst 1mmol% Ru and Ligand, toluene (1 mL), time (18 h), temperature (120 °C), analyzed by GC.

Table 2. The effects of solvents and bases on the alkylation of **1a** with **2a**.[a]



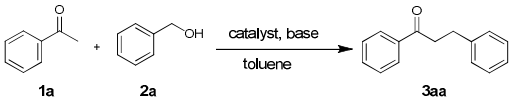
Entry	Solvent	Base	Yield (%)
1	*tert*-Amyl alcohol	Cs_2CO_3	68
2	Toluene	Cs_2CO_3	75
3	1,4-Dioxane	Cs_2CO_3	55
4	DMSO	Cs_2CO_3	12
5	Xylene	Cs_2CO_3	63
6[b]	Toluene	Cs_2CO_3	56
7[c]	Toluene	Cs_2CO_3	75
8	Toluene	Na_2CO_3	Trace
9	Toluene	K_2CO_3	Trace
10	Toluene	NaOH	57
11	Toluene	t-BuOK	30
12	Toluene	KOH	32

[a] Reaction conditions: **1a** (1 mmol), **2a** (1.1 mmol), base (1 mmol), catalyst 1mmol% Ru, $[RuCl_2(\eta^6\text{-p-cymene})]_2$/**L1** = 1/2, solvent (1 mL), time (6 h), temperature (120 °C), analyzed by GC.

[b] 100 μL water was added.

[c] 1 mmol anhydrous Na_2SO_4 was added.

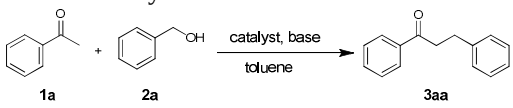
Table 3. The effects of **1a**/base ratios on the alkylation of **1a** with **2a**.[a]



Entry 1	**1a**/base	Yield
1	1/1	75
2	1/0.6	75
3	1/0.5	72
4	1/0.4	68
5	1/0.2	59
6	1/0	n. d

[a] Reaction conditions: **1a** (1 mmol), **2a** (1.1 mmol), Cs_2CO_3 (0 -1 mmol), catalyst 1mmol% Ru, $[RuCl_2(\eta^6\text{-p-cymene})]_2$/**L1** = 1/2, toluene (1 mL), time (6 h), temperature (120 °C), analyzed by GC.

Table 4. The effects of time, catalyst loadings and temperature on the alkylation of **1a** with **2a**.[a]



Entry	Ru loading (mmol%)	Time (h)	Yield (%)
1	1	6	75
2	1	12	84

3	1	18	87
4	1	24	87
5	0.5	18	78
6	2	18	85
7[b]	1	18	72

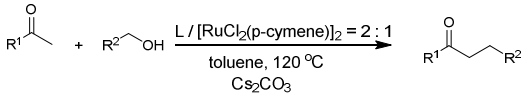
[a] Reaction conditions: **1a** (1 mmol), **2a** (1.1 mmol), Cs_2CO_3 (0.6 mmol), $[RuCl_2(\eta^6\text{-p-cymene})]_2$/**L1** = 1/2, toluene (1 mL), temperature(120 °C), analyzed by GC.

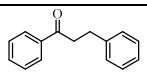
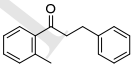
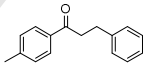
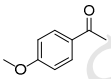
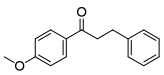
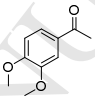
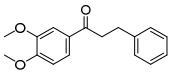
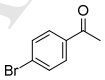
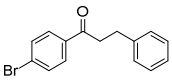
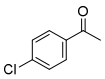
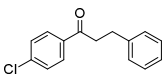
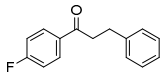
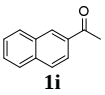
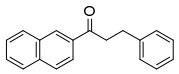
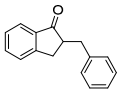
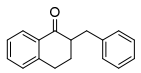
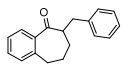
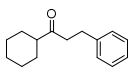
[b] Reaction temperature: 110 °C.

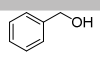
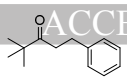
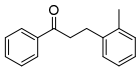
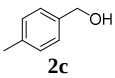
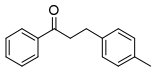
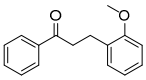
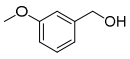
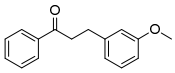
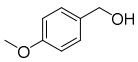
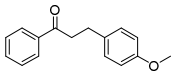
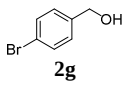
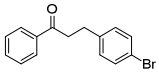
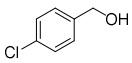
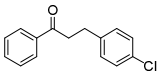
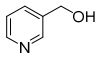
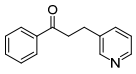
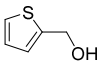
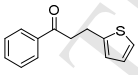
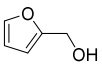
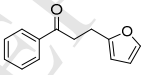
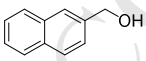
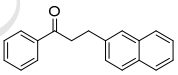
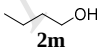
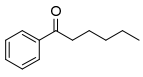
The influence of solvents and bases was also explored (Table 2). The highest yield (75%) was obtained in toluene, although *tert*-amyl alcohol was also reported to be a suitable solvent for similar systems.[5d,e] The reaction could not tolerate water because addition of 100 μL of water led to a dramatic decrease in the product yield (Table 2, entry 6). Conversely, addition of 1 mmol anhydrous Na_2SO_4 did not improve the product yield (Table 2, entry 7). Cs_2CO_3 was proved to be the best base (75% yield, Table 2, entry 2). Bases such as Na_2CO_3 and K_2CO_3 afforded only a trace of the product **3aa** (Table 2, entries 8-9) and no product **3aa** was formed in the absence of base (Table 3, entry 6). The optimum **1a**/base ratio was fixed to be 1/0.6 (Table 3). Finally the effects of time, $[RuCl_2(\eta^6\text{-p-cymene})]_2$ loading and temperature were examined (Table 4). We monitored the reaction every 6 hours (Table 4, entries 1-4) and observed that the maximum yield for **3aa** was obtained after 18 hours. Doubling or halving the catalyst loading made little difference (Table 4, entries 5-6). Decreasing the reaction temperature from 120 °C to 110 °C led to a yield decrease from 87% to 72% (Table 4, entry 7). Therefore, 120 °C was the suitable temperature, which proved that our catalytic system could achieve the reaction well at relatively lower temperature compared to reported work (140 °C).[4e]

With the optimal reaction conditions in hand, we subsequently investigated a range of substrates (Table 5). Acetophenone bearing electron-donating methyl (**1b**-**1c**) or methoxy (**1d**) gave the corresponding products (**3ba**-**3da**) in yields of 85%-96% (Table 5, entries 2-4). The somewhat hindered o-methylacetophenone **1b** was at the lower end of that yield range. The pharmaceutically interesting, electron-rich dimethoxy analogue (**1e**) also gave the desired product (**3ea**) in 85% yield (Table 5, entry 5). Reaction of acetophenone bearing electron-withdrawing substituents, bromine (**1f**) and chlorine (**1g**), proceeded well (Table 5, entries 6-7), but the more electron-deficient fluorine analogue (**1h**) gave the corresponding product (**3ha**) in a reduced 61% yield (Table 5, entry 8). It may be due to the fact that the withdrawal of electron density from the carbonyl of the donor acetophenone weakens the coordination to ruthenium and/or slows the subsequent condensation with acceptor benzaldehyde (Scheme 1). Notably, in addition to methyl ketones, three cyclic ketones (**1j**-**1l**) could also be successfully transformed into the corresponding products (**3ja**-**3la**) (Table 5, entries 10-12). Besides, the steric hindered alkyl ketones such as cyclohexyl methyl ketone (**1m**) or tert-butyl methyl ketone (**1n**) could also be adapted in this reaction with lower yields (Table 5, entries 13 and 14). The reaction was tolerant of methyl, methoxy and halide substitution on the benzylic alcohols (**2b**-**2h**) (Table 5, entries 15-21), but less so of substrates bearing strongly coordinating heteroatoms (**2i**–**2k**) (Table 5, entries 22-24), presumably due to the unproductive coordination to the ruthenium catalyst. In addition to aromatic alcohols, the product of butan-1-ol (**2m**) addition could also be isolated, albeit in a low yield (Table 5, entry 26).

Table 5. $[RuCl_2(\eta^6\text{-p-cymene})]_2$/**L1**-Catalyzed α-alkylation of ketones with alcohols[a]



Entry	Ketone	Alcohol	Product	Yield (%)
1	 **1a**	 **2a**	 **3aa**	92
2	 **1b**	 **2a**	 **3ba**	85
3	 **1c**	 **2a**	 **3ca**	94
4	 **1d**	 **2a**	 **3da**	96
5	 **1e**	 **2a**	 **3ea**	85
6	 **1f**	 **2a**	 **3fa**	92
7	 **1g**	 **2a**	 **3ga**	92
8	 **1h**	 **2a**	 **3ha**	61
9	 **1i**	 **2a**	 **3ia**	87
10	 **1j**	 **2a**	 **3ja**	76
11	 **1k**	 **2a**	 **3ka**	80
12	 **1l**	 **2a**	 **3la**	94
13	 **1m**	 **2a**	 **3ma**	40

14	 **1n**	 **2a**	 **3na**	23	
15	 **1a**	 **2b**	 **3ab**	78	
16	 **1a**	 **2c**	 **3ac**	88	
17	 **1a**	 **2d**	 **3ad**	82	
18	 **1a**	 **2e**	 **3ae**	78	
19	 **1a**	 **2f**	 **3af**	89	
20	 **1a**	 **2g**	 **3ag**	90	
21	 **1a**	 **2h**	 **3ah**	79	
22	 **1a**	 **2i**	 **3ai**	52	
23	 **1a**	 **2j**	 **3aj**	61	
24	 **1a**	 **2k**	 **3ak**	48	
25	 **1a**	 **2l**	 **3al**	90	
26	 **1a**	 **2m**	 **3am**	32	

[a] Reaction conditions: ketones (1 mmol), alcohol (1.1 mmol), Cs_2CO_3 (0.6 mmol), catalyst 1mmol% Ru, $[RuCl_2(\eta^6\text{-p-cymene})]_2$/**L1** = 1/2, toluene (1 mL), temperature (120 °C), time (18 h), isolated yield.

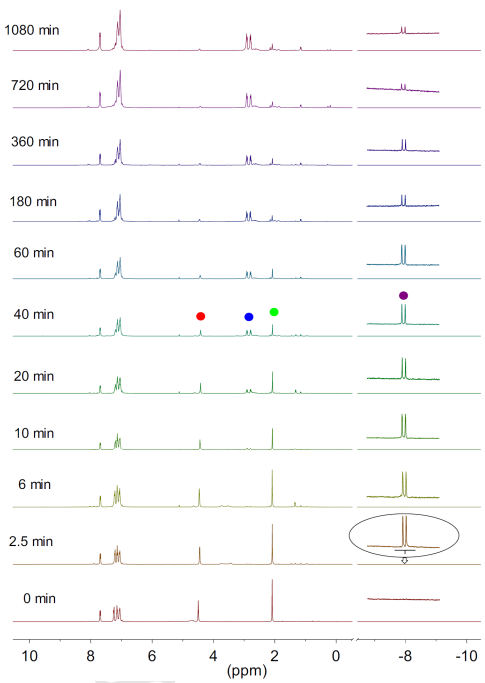
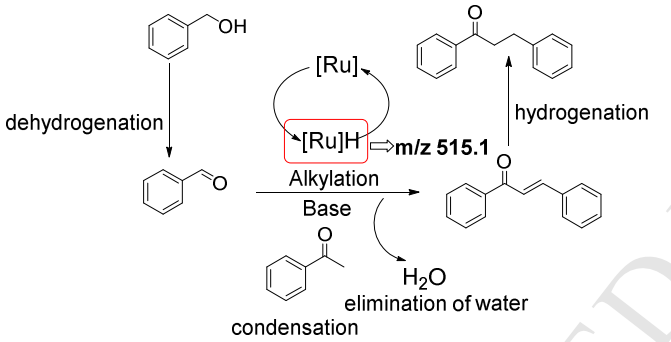


Fig. 2. ^{1}H NMR monitoring of the reaction: **1a** (1 mmol), **2a** (1.1 mmol), Cs_2CO_3 (0.6 mmol), catalyst 5mmol% Ru, $[RuCl_2(\eta^6\text{-p-cymene})]_2$/**L1** = 1/2, toluene-$d_8$ (1 mL), temperature (120 °C). Red dot: **2a**; Blue dot: **3aa**; Green dot: **1a** and the residual solvent peak of toluene-d_8; Purple dot: hydride signal of Ru-hydride intermediate (located at -8.01 ppm and zoomed in).

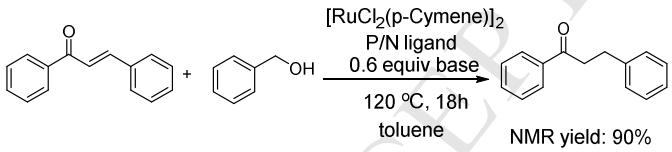
Fig. 3. (a) The positive-ion ESI-MS spectrum (black) and the calculated isotopic patterns (grey) of $[Ru(\eta^6\text{-p-cymene})(\kappa^2\text{-L1})H]^+$ detected in the reaction. (b) The possible structure of $[Ru(\eta^6\text{-p-cymene})(\kappa^2\text{-L1})H]^+$. (c) The

positive-ion ESI-MS spectrum (black) and the calculated isotopic patterns (grey) of $[Ru(\eta^6\text{-p-cymene})(\kappa^2\text{-}\mathbf{L1})Cl]^+$ detected in the reaction. (d) The possible structure of $[Ru(\eta^6\text{-p-cymene})(\kappa^2\text{-}\mathbf{L1})Cl]^+$.

Information concerning the mechanism of reaction was gained by *in situ* monitoring its ^{1}H NMR spectra (Fig. 2). A Ru-H signal was detected at δ_H = -8.01 ppm (d, $^2J_{PH}$ = 43 Hz) and persisted throughout the reaction. The NMR sample was analyzed by ESI-MS and a cluster of ions corresponding to $[Ru(\eta^6\text{-p-cymene})(\kappa^2\text{-}\mathbf{L1})H]^+$ at *m*/*z* = 515.1 was detected (Figs. 3a and 3b). Notably, the Ru-hydride intermediate was generated quickly and persisted throughout the 18 h reaction (Figs. S1-S10 in Supporting Information), and proved to be constant in toluene after cooling to ambient temperature even after 50 days (Figs. S11-S12 in Supporting Information). Compared with the ruthenium hydride intermediate observed for the conversion of ethanol to n-butanol (persisted for 40 min)[8i] and a Ru-H species detected in a similar ruthenacycle catalyzed asymmetric hydrogen transfer reaction (persisted for 30 min),[14] we suggest, therefore, that our putative 18 electron $[Ru(\eta^6\text{-p-cymene})(\kappa^2\text{-}\mathbf{L1})H]^+$ intermediate may be different and obviously more stable than those observed previously. To probe the formation of this intermediate further, we stirred the reaction for 30 min at room temperature and observed a cationic species in its ESI-MS, corresponding to the formation of the precatalyst $[Ru(\eta^6\text{-p-cymene})(\kappa^2\text{-}\mathbf{L1})Cl]^+$ at *m*/*z* = 549.1 (Figs. 3c and 3d).



Scheme 1. Proposed reaction mechanism for the α-alkylation of ketone with alcohol.



Scheme 2. The catalytic hydrogen transfer between α,β-unsaturated ketone with benzyl alcohol.

Careful investigation of those ^{1}H NMR spectra during the course of the reaction revealed the appearance and disappearance of the intermediate species proposed in Scheme 1. All three steps proceed almost simultaneously with α,β-unsaturated ketone, benzaldehyde, and 1,3-diphenylpropan-1-one detected **(3aa)** after only 2.5 minutes of heating (Figs. S13-S15 in Supporting Information). The last step, the reaction of α,β-unsaturated ketone with benzyl alcohol (Scheme 2) was examined separately and, indeed, afforded the transfer hydrogenation product in 90% yield.

3. Conclusions

In the work reported here, we have demonstrated that the α-alkylation of ketones with alcohols can be efficiently and cleanly promoted by a $[RuCl_2(\eta^6\text{-p-cymene})]_2$/**L1** catalytic system for a diverse array of substrates. *In situ* monitoring by ^{1}H NMR and ESI-MS has revealed the existence of a stable **L1**-coordinated ruthenium hydride intermediate $[Ru(\eta^6\text{-p-cymene})(\kappa^2\text{-}\mathbf{L1})H]^+$ and organic intermediates consistent with a three-step dehydrogenation, alkylation and hydrogenation pathway. Further investigation of this semi-labile ligand system for the hydrogen transfer catalysis is underway in our laboratory.

4. Experimental

4.1. General

All reactions were carried out under a nitrogen atmosphere using standard Schlenk-techniques. Solvents were used without further purification. ^{1}H NMR and ^{13}C NMR spectra were recorded at ambient temperature on a Varian UNITYplus-300, 400 or 600 spectrometer. ^{1}H NMR and ^{13}C NMR chemical shifts were referenced to the solvent signal in $CDCl_3$, DMSO-d_6 or Toluene-d_8. Electrospray ion mass spectra (ESI-MS) were acquired on a micrOTOF-Q III. GC measurements were recorded on an Agilent 7820A Gas Chromatograph with an Agilent HP-5 chromatographic column and N_2 as mobile phase. The LC-MS was recorded using a Rapid Resolution HT-3 chromatographic column on an Agilent 1260 Infinity Liquid Chromatograph with 6120 Quadrupole Mass Spectrometer and MeCN as mobile phase. $[Ru(\eta^6\text{-p-cymene})Cl_2]_2$ (purity > 97%) was purchased from Aladdin Industrial Corporation. Other reagents were commercially available and used without further purification.

4.2. Synthesis and characterization of L1-L6

*4.2.1. Synthesis of **L1-L3***. Ligands **L1-L3** were prepared according to the literature procedures.[8e,15] The ^{1}H NMR spectra and EA data were included in the Supporting Information. (Figs. S16-S18).

*4.2.2. Synthesis of **L4***. A mixture of 4-methoxypyridin-2-amine (1.32 g, 10.6 mmol) and triethylamine (1.45 mL, 10.5 mmol) was dissolved in toluene (50 mL) at room temperature in a two neck flask under a N_2 atmosphere and Ph_2PCl (2.0 mL, 10.6 mmol) was then added dropwise over 10 minutes. The solution was allowed to warm to 80 °C, stirred overnight and the triethylamine hydrochloride suspension formed was filtered and washed with 25 mL toluene. The combined solvents were evaporated yielding yellow oil. Methanol was added with stirring and the resulting white product **L4** was filtered, washed with a small amount of methanol and diethyl ether (2 mL x 3) and dried under vacuum for 24 h. Yield: 1.15 g (36 %). ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 7.84 (d, J = 5.8 Hz, 1H), 7.65 – 7.24 (m, 11H), 6.49 (d, J = 1.1 Hz, 1H), 6.43 – 6.19 (m, 1H), 3.74 (s, 3H). ^{13}C NMR (151 MHz, $CDCl_3$, ppm): δ 167.34, 160.55 (d, J = 21.3 Hz), 148.99, 139.45 (d, J = 10.9 Hz), 131.22 (d, J = 20.8 Hz), 129.16, 128.54 (d, J = 6.6 Hz), 103.49, 92.74 (d, J = 17.6 Hz), 55.00. ^{31}P NMR (243 MHz, $CDCl_3$, ppm): δ 25.52 (Fig. S19 in Supporting Information). Anal. Calcd. (%) for $C_{18}H_{17}N_2OP$: C 70.12, H 5.56, N 9.09; found: C 70.20, H 5.64, N 9.28.

*4.2.3. Synthesis of **L5***. Ligand **L5** was prepared using the same procedure as for **L4**. Yield: 42%; white solid. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 8.01 (d, J = 5.4 Hz, 1H), 7.84 (d, J = 8.8 Hz, 1H), 7.46 – 7.33 (m, 10H), 6.99 (s, 1H), 6.78 (d, J = 5.2 Hz, 1H). ^{13}C NMR (151 MHz, $CDCl_3$, ppm): δ 159.97 (d, J = 22.4 Hz), 148.90, 145.22, 138.88 (d, J = 10.8 Hz), 131.26 (d, J = 20.9 Hz), 129.39, 128.64 (d, J = 6.7 Hz), 115.49, 108.64 (d, J = 17.7 Hz).^{31}P NMR (243 MHz, $CDCl_3$, ppm): δ 26.71 (Fig. S20 in Supporting Information). Anal. Calcd. (%) for $C_{17}H_{14}ClN_2P$: C 65.29; H, 4.51; N, 8.96; found: C 65.38, H 4.60, N 9.16.

*4.2.4. Synthesis of **L6***. Ligand **L6** was prepared using the same procedure as for **L4**. Yield: 26%; white solid. ^{1}H NMR (400 MHz, DMSO-d_6, ppm)) δ 7.52 (d, J = 9.2 Hz, 1H), 7.48 – 7.32

(m, 11H), 6.76 (d, *J* = 8.2 Hz, 1H), 6.54 (d, *J* = 7.2 Hz, 1H), 2.25 (s, 3H). ^{13}C NMR (151 MHz, DMSO-d_6, ppm): δ 158.47 (d, *J* = 17.1 Hz), 156.16, 140.74 (d, *J* = 14.3 Hz), 137.79, 131.26 (d, *J* = 21.4 Hz), 128.83, 128.43 (d, *J* = 6.5 Hz), 113.46, 107.13 (d, *J* = 8.3 Hz), 24.09. ^{31}P NMR (243 MHz, DMSO-d_6, ppm): δ 22.06 (Fig. S21 in Supporting Information). Anal. Calcd. (%) for $C_{18}H_{17}N_2P$: C, 73.96; H, 5.86; N, 9.58; found: C 73.92; H 5.92; N 9.78.

4.3. General procedure for screening reaction conditions.

Base and solvent were placed in a Schlenk tube under a N_2 atmosphere. Each Ru precursor, ligand, **1a** and **2a** were added and stirred for the required time at proper reaction temperature. The reaction mixture was cooled to room temperature. Benzophenone (182 mg, 1.0 mmol, internal standard) was added and the mixture diluted with ethyl acetate (18 mL). An aliquot of the reaction solution was analyzed by GC.

4.4. General procedure for the [$RuCl_2(\eta^6$-p-cymene)]$_2$/L1-Catalyzed α-alkylation of ketones with alcohols

Cs_2CO_3 (0.6 mmol, 195.6 mg) and toluene (1 mL) were added to a Schlenk tube under a N_2 atmosphere. [$RuCl_2(\eta^6$-p-cymene)]$_2$ (0.005 mmol, 3.1 mg), **L1** (0.01mmol, 2.8 mg), alcohols (1.1 mmol,) and ketones (1.0 mmol) were added in that order and the Schlenk tube was closed and stirred at 120 ^{o}C for 18h. The reaction mixture was cooled to room temperature, quenched with water and extracted with ethyl acetate (20 mL x 3). The combined extracts were dried over anhydrous sodium sulfate and concentrated in vacuo. The product was purified by column chromatography using petroleum ether/ethyl acetate as eluent to give the corresponding product (Figs. S22-S47 in Supporting Information).

4.4.1. 1,3-diphenylpropan-1-one (***3aa***).[5d] White solid. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 7.98 (d, *J* = 7.5 Hz, 2H), 7.62 (d, *J* = 7.3 Hz, 1H), 7.51 (t, *J* = 7.6 Hz, 2H), 7.28 (d, *J* = 4.3 Hz, 4H), 7.18 (d, *J* = 3.5 Hz, 1H), 3.38 (d, *J* = 7.4 Hz, 2H), 2.94 (t, *J* = 7.5 Hz, 2H). ^{13}C NMR (101 MHz, DMSO-d_6, ppm): δ 199.32, 141.42, 136.78, 133.30, 128.88, 128.57, 128.44, 128.10, 126.03, 39.65, 29.66.

4.4.2. 3-phenyl-1-(o-tolyl)propan-1-one (***3ba***).[5d] White solid. ^{1}H NMR (400 MHz, DMSO-d_6 , ppm): δ 7.74 (d, *J* = 7.6 Hz, 1H), 7.40 (t, *J* = 7.4 Hz, 1H), 7.28 (dd, *J* = 13.7, 7.0 Hz, 6H), 7.17 (t, *J* = 6.3 Hz, 1H), 3.25 (t, *J* = 7.4 Hz, 2H), 2.91 (t, *J* = 7.4 Hz, 2H), 2.34 (s, 3H). ^{13}C NMR (151 MHz, DMSO-d_6, ppm): δ 203.49, 141.26, 138.11, 136.95, 131.70, 131.27, 128.62, 128.51, 128.41, 126.02, 126.01, 42.59, 29.87, 20.73.

4.4.3. 3-phenyl-1-(p-tolyl)propan-1-one (***3ca***).[5d] White solid. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 7.88 (d, *J* = 8.0 Hz, 2H), 7.29 (dd, *J* = 16.7, 6.1 Hz, 6H), 7.18 (dd, *J* = 8.4, 4.2 Hz, 1H), 3.34 (t, *J* = 6.7 Hz, 2H), 2.93 (t, *J* = 7.5 Hz, 2H), 2.37 (s, 3H). ^{13}C NMR (101 MHz, DMSO-d_6, ppm): δ 198.80, 143.60, 141.46, 134.32, 129.40, 128.55, 128.42, 128.22, 126.01, 39.53, 29.73, 21.30.

4.4.4. 1-(4-methoxyphenyl)-3-phenylpropan-1-one (***3da***).[5d] White solid. ^{1}H NMR (400 MHz, DMSO-d_6, ppm) δ 7.96 (d, *J* = 8.7 Hz, 2H), 7.27 (d, *J* = 4.3 Hz, 4H), 7.17 (dd, *J* = 8.5, 4.3 Hz, 1H), 7.02 (d, *J* = 8.7 Hz, 2H), 3.82 (s, 3H), 3.29 (t, *J* = 7.5 Hz, 2H), 2.92 (t, *J* = 7.5 Hz, 2H). ^{13}C NMR (101 MHz, DMSO-d_6): δ 197.66, 163.23, 141.54, 130.42, 129.75, 128.56, 128.42, 126.00, 114.03, 55.68, 39.28, 29.84.

4.4.5. 1-(3,4-dimethoxyphenyl)-3-phenylpropan-1-one (***3ea***).[16] Yellow solid. ^{1}H NMR (400 MHz, DMSO-d_6, ppm) δ 7.71 – 7.60 (m, 1H), 7.46 (s, 1H), 7.27 (d, *J* = 4.2 Hz, 4H), 7.17 (dd, *J* = 8.4, 4.2 Hz, 1H), 7.03 (d, *J* = 8.4 Hz, 1H), 3.83 (s, 3H), 3.80 (s, 3H), 3.30 (t, *J* = 7.5 Hz, 2H), 2.93 (t, *J* = 7.5 Hz, 2H).^{13}C NMR (151 MHz, DMSO-d_6, ppm): δ 197.74, 153.20, 148.75, 141.58, 129.75, 128.60, 128.44, 126.02, 122.78, 111.02, 110.39, 55.89, 55.66, 39.23, 29.98.

4.4.6. 1-(4-bromophenyl)-3-phenylpropan-1-one (***3fa***).[5d] Yellow solid. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 7.91 (d, *J* = 8.3 Hz, 2H), 7.71 (d, *J* = 8.3 Hz, 2H), 7.27 (d, *J* = 4.2 Hz, 4H), 7.17 (dd, *J* = 8.4, 4.1 Hz, 1H), 3.34 (d, *J* = 7.6 Hz, 2H), 2.92 (t, *J* = 7.4 Hz, 2H). ^{13}C NMR (151 MHz, DMSO-d_6, ppm): δ 198.80, 141.51, 135.99, 132.17, 130.40, 128.79, 128.68, 127.63, 126.30, 39.89, 29.80.

4.4.7. 1-(4-chlorophenyl)-3-phenylpropan-1-one (***3ga***).[5d] Yellow solid. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 7.99 (d, *J* = 8.4 Hz, 2H), 7.58 (d, *J* = 8.4 Hz, 2H), 7.27 (d, *J* = 4.2 Hz, 4H), 7.18 (dd, *J* = 8.4, 4.2 Hz, 1H), 3.37 (t, *J* = 7.6 Hz, 2H), 2.93 (t, *J* = 7.5 Hz, 2H). ^{13}C NMR (101 MHz, DMSO-d_6, ppm): δ 198.36, 141.28, 138.21, 135.43, 130.05, 128.97, 128.56, 128.43, 126.05, 39.66, 29.55.

4.4.8. 1-(4-fluorophenyl)-3-phenylpropan-1-one (***3ha***).[5d] Yellow oil. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 8.06 (dd, *J* = 8.3, 5.8 Hz, 2H), 7.39-7.22 (m, 6H), 7.17 (dd, *J* = 8.3, 4.3 Hz, 1H), 3.35 (t, *J* = 7.2 Hz, 2H), 2.93 (t, *J* = 7.5 Hz, 2H). ^{13}C NMR (101 MHz, DMSO-d_6, ppm): δ 197.88, 165.16 (d, *J* = 251.6 Hz), 141.34, 133.51 (d, *J* = 2.8 Hz), 131.09 (d, *J* = 9.4 Hz), 128.56, 128.42, 126.03, 115.82 (d, *J* = 21.8 Hz), 39.59, 29.62.

4.4.9. 1-(naphthalen-2-yl)-3-phenylpropan-1-one (***3ia***).[17] Yellow solid. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 8.71 (s, 1H), 8.12 (d, *J* = 7.9 Hz, 1H), 7.99 (d, *J* = 10.9 Hz, 3H), 7.63 (m,2H), 7.30 (q, *J* = 7.5 Hz, 4H), 7.19 (t, *J* = 6.8 Hz, 1H), 3.51 (t, *J* = 7.5 Hz, 2H), 3.00 (t, *J* = 7.5 Hz, 2H). ^{13}C NMR (151 MHz, DMSO-d_6, ppm): δ 199.19, 141.46, 135.18, 134.02, 132.40, 130.06, 129.75, 128.71, 128.60, 128.43, 128.40, 127.78, 127.02, 126.02, 123.67, 39.77, 29.79.

4.4.10. 2-benzyl-2,3-dihydro-1H-inden-1-one (***3ja***).[5d] Pale-yellow oil. 1H NMR (400 MHz, DMSO-d_6, ppm): δ 7.65 (dd, *J* = 10.9, 7.7 Hz, 2H), 7.52 (d, *J* = 7.6 Hz, 1H), 7.41 (t, *J* = 7.4 Hz, 1H), 7.34 – 7.23 (m, 4H), 7.20 (d, *J* = 5.6 Hz, 1H), 3.22 – 3.08 (m, 2H), 3.08 – 2.99 (m, 1H), 2.80 (dd, *J* = 16.8, 3.1 Hz, 1H), 2.68 (dd, *J* = 13.6, 9.9 Hz, 1H). ^{13}C NMR (151 MHz, DMSO-d_6, ppm): δ 207.30, 153.88, 139.74, 136.29, 135.09, 129.06, 128.52, 127.63, 127.11, 126.33, 123.37, 48.24, 36.11, 31.78.

4.4.11. 2-benzyl-3,4-dihydronaphthalen-1(2H)-one (***3ka***).[18] Yellow oil. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 7.91 (d, J = 7.7 Hz, 1H), 7.53 (t, *J* = 7.3 Hz, 1H), 7.38 – 7.15 (m, 7H), 3.29 (dd, *J* = 13.7, 4.2 Hz, 1H), 2.99 – 2.78 (m, 3H), 2.62 (dd, *J* = 13.7, 9.2 Hz, 1H), 2.05 – 1.89 (m, 1H), 1.77 – 1.58 (m, 1H). ^{13}C NMR (101 MHz, DMSO-d_6, ppm): δ 198.82, 144.42, 140.04, 133.53, 132.16, 129.31, 129.13, 128.42, 126.81, 126.70, 126.13, 48.55, 35.22, 28.04, 27.49.

4.4.12. 6-benzyl-6,7,8,9-tetrahydro-5H-benzo[7]annulen-5-one (***3la***).[19] Yellow oil. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 7.50 – 7.38 (m, 2H), 7.34 – 7.11 (m, 7H), 3.28 – 3.18 (m, 1H), 3.15 (dd, *J* = 13.5, 6.7 Hz, 1H), 3.10 – 2.97 (m, 1H), 2.89 (dd, *J* = 15.6, 4.8 Hz, 1H), 2.68 (dd, *J* = 13.5, 6.9 Hz, 1H), 2.05 – 1.92 (m, 1H), 1.83 (dt, *J* = 20.8, 10.3 Hz, 1H), 1.59 – 1.38 (m, 2H).^{13}C NMR (151 MHz, DMSO-d_6, ppm): δ 205.88, 142.34, 140.28, 139.62, 131.50, 130.15, 129.05, 128.31, 127.81, 126.39, 126.03, 50.60, 36.46, 32.83, 29.49, 25.31.

4.4.13. 1-cyclohexyl-3-phenylpropan-1-one (**3ma**).[20] Yellow oil.^{1}H NMR (400 MHz, DMSO-d_6): δ 7.25 (t, *J* = 7.3 Hz, 2H), 7.19 (d, *J* = 7.8 Hz, 2H), 7.14 (d, *J* = 7.0 Hz, 1H), 2.82 – 2.69 (m,

4H), 2.34 (t, *J* = 8.8 Hz, 1H), 1.74 (d, *J* = 10.2 Hz, 2H), 1.70 – 1.63 (m, 2H), 1.58 (d, J = 11.7 Hz, 1H), 1.27 – 1.09 (m, 5H). ^{13}C NMR (151 MHz, DMSO-d_6, ppm): δ 212.34, 141.49, 128.35, 125.90, 49.77, 41.44, 29.24, 28.05, 25.64, 25.27.

*4.4.14. 4,4-dimethyl-1-phenylpentan-3-one (**3na**).*[5d] Yellow oil. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 7.25 (t, *J* = 7.3 Hz, 2H), 7.20 (d, *J* = 7.2 Hz, 2H), 7.16 (t, *J* = 7.1 Hz, 1H), 2.84 (t, *J* = 7.0 Hz, 2H), 2.74 (t, *J* = 7.0 Hz, 2H), 1.03 (s, 9H). ^{13}C NMR (151 MHz, DMSO-d_6, ppm): δ 214.25, 141.59, 128.45, 128.34, 125.92, 43.57, 37.71, 29.60, 26.12.

*4.4.15.1-phenyl-3-(o-tolyl)propan-1-one (**3ab**).*[5a] Colorless oil. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 7.99 (d, *J* = 7.6 Hz, 2H), 7.63 (t, *J* = 7.3 Hz, 1H), 7.52 (t, *J* = 7.5 Hz, 2H), 7.19 (d, *J* = 5.9 Hz, 1H), 7.16 – 7.05 (m, 3H), 3.31 (t, *J* = 7.6 Hz, 2H), 2.91 (t, *J* = 7.5 Hz, 2H), 2.28 (s, 3H). ^{13}C NMR (151 MHz, DMSO-d_6, ppm): δ 199.40, 139.46, 136.75, 135.85, 133.29, 130.10, 128.86, 128.69, 128.12, 126.12, 126.05, 38.47, 26.99, 19.15.

*4.4.16. 1-phenyl-3-(p-tolyl)propan-1-one (**3ac**).*[5d] Colorless oil. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 7.97 (d, *J* = 7.6 Hz, 2H), 7.62 (t, *J* = 7.3 Hz, 1H), 7.51 (t, *J* = 7.5 Hz, 2H), 7.15 (d, *J* = 7.7 Hz, 2H), 7.07 (d, *J* = 7.7 Hz, 2H), 3.32 (t, *J* = 7.5 Hz, 2H), 2.89 (t, *J* = 7.4 Hz, 2H), 2.24 (s, 3H). ^{13}C NMR (151 MHz, DMSO-d_6, ppm): δ 199.35, 138.26, 136.79, 134.91, 133.27, 128.99, 128.87, 128.41, 128.07, 39.76, 29.26, 20.78.

*4.4.17. 3-(2-methoxyphenyl)-1-phenylpropan-1-one (**3ad**).*[4e] White solid. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 7.97 (d, *J* = 7.6 Hz, 2H), 7.62 (t, *J* = 7.3 Hz, 1H), 7.51 (t, *J* = 7.5 Hz, 2H), 7.18 (t, *J* = 7.4 Hz, 2H), 6.94 (d, *J* = 8.2 Hz, 1H), 6.86 (t, *J* = 7.3 Hz, 1H), 3.78 (s, 3H), 3.26 (t, *J* = 7.6 Hz, 2H), 2.90 (t, *J* = 7.5 Hz, 2H). ^{13}C NMR (101 MHz, DMSO-d_6, ppm): δ 199.56, 157.28, 136.73, 133.24, 129.79, 128.97, 128.86, 128.06, 127.56, 120.40, 110.68, 55.36, 38.28, 24.87.

*4.4.18. 3-(3-methoxyphenyl)-1-phenylpropan-1-one (**3ae**).*[4e] White solid. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 7.99 (d, *J* = 7.6 Hz, 2H), 7.63 (t, *J* = 7.3 Hz, 1H), 7.52 (t, *J* = 7.5 Hz, 2H), 7.18 (t, *J* = 7.8 Hz, 1H), 6.85 (d, *J* = 7.9 Hz, 2H), 6.74 (d, *J* = 7.6 Hz, 1H), 3.72 (s, 3H), 3.38 (d, *J* = 7.4 Hz, 2H), 2.91 (t, *J* = 7.4 Hz, 2H). ^{13}C NMR (101 MHz, DMSO-d_6, ppm): δ 199.34, 159.46, 143.01, 136.79, 133.30, 129.43, 128.88, 128.11, 120.80, 114.27, 111.48, 55.06, 39.58, 29.71.

*4.4.19. 3-(4-methoxyphenyl)-1-phenylpropan-1-one (**3af**).*[4e] White solid. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 7.97 (d, *J* = 7.6 Hz, 2H), 7.62 (t, *J* = 7.2 Hz, 1H), 7.51 (t, *J* = 7.5 Hz, 2H), 7.18 (d, *J* = 8.3 Hz, 2H), 6.83 (d, *J* = 8.4 Hz, 2H), 3.70 (s, 3H), 3.31 (d, *J* = 7.4 Hz, 2H), 2.88 (t, *J* = 7.4 Hz, 2H). ^{13}C NMR (101 MHz, DMSO-d_6, ppm): δ 199.43, 157.68, 136.81, 133.27, 133.23, 129.50, 128.87, 128.08, 113.85, 55.14, 39.97, 28.83.

*4.4.20. 3-(4-bromophenyl)-1-phenylpropan-1-one (**3ag**).*[5d] White solid. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 7.98 (d, *J* = 7.6 Hz, 2H), 7.62 (d, *J* = 7.3 Hz, 1H), 7.51 (t, *J* = 7.6 Hz, 2H), 7.46 (d, *J* = 8.2 Hz, 2H), 7.26 (d, *J* = 8.1 Hz, 2H), 3.38 (t, *J* = 7.4 Hz, 2H), 2.92 (t, *J* = 7.4 Hz, 2H). ^{13}C NMR (101 MHz, DMSO-d_6) δ 199.11, 140.92, 136.71, 133.34, 131.22, 130.91, 128.88, 128.09, 119.05, 39.31, 28.94.

*4.4.21. 3-(4-chlorophenyl)-1-phenylpropan-1-one (**3ah**).*[5d] White solid. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 7.98 (d, *J* = 7.5 Hz, 2H), 7.62 (d, *J* = 7.3 Hz, 1H), 7.52 (t, *J* = 7.6 Hz, 2H), 7.32 (s, 4H), 3.38 (t, *J* = 7.4 Hz, 2H), 2.93 (t, *J* = 7.4 Hz, 2H). ^{13}C NMR (101 MHz, DMSO-d_6, ppm): δ 199.13, 140.48, 136.72, 133.34, 130.64, 130.49, 128.88, 128.31, 128.09, 39.39, 28.89.

*4.4.22. 1-phenyl-3-(pyridin-3-yl)propan-1-one (**3ai**).*[4e] White solid. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 8.52 (s, 1H), 8.39 (d, *J* = 4.2 Hz, 1H), 7.99 (d, *J* = 7.6 Hz, 2H), 7.71 (d, *J* = 7.7 Hz, 1H), 7.63 (t, *J* = 7.3 Hz, 1H), 7.52 (t, *J* = 7.6 Hz, 2H), 7.30 (dd, *J* = 7.5, 4.9 Hz, 1H), 3.43 (t, *J* = 7.4 Hz, 2H), 2.95 (t, *J* = 7.3 Hz, 2H).^{13}C NMR (151 MHz, DMSO-d_6, ppm): δ 199.10, 149.94, 147.34, 136.86, 136.68, 136.10, 133.38, 128.89, 128.10, 123.51, 39.13 26.72.

*4.4.23. 1-phenyl-3-(thiophen-2-yl)propan-1-one (**3aj**).*[4e] Yellow oil. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.97 (d, *J* = 7.6 Hz, 2H), 7.57 (t, *J* = 7.3 Hz, 1H), 7.46 (t, *J* = 7.6 Hz, 2H), 7.13 (d, *J* = 4.9 Hz, 1H), 6.97 – 6.89 (m, 1H), 6.87 (s, 1H), 3.40 – 3.35 (m, 2H), 3.33 – 3.27 (m, 2H). ^{13}C NMR (101 MHz, DMSO-d_6, ppm): δ 198.80, 143.87, 136.69, 133.40, 128.90, 128.11, 127.02, 124.94, 123.84, 39.82, 23.77.

*4.4.24. 3-(furan-2-yl)-1-phenylpropan-1-one (**3ak**).*[5d] Yellow oil. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 8.00 (d, *J* = 7.6 Hz, 2H), 7.64 (t, *J* = 7.2 Hz, 1H), 7.58 – 7.42 (m, 3H), 6.34 (s, 1H), 6.14 (s, 1H), 3.37 (d, *J* = 7.5 Hz, 2H), 2.96 (t, *J* = 7.3 Hz, 2H). ^{13}C NMR (101 MHz, DMSO-d_6, ppm): δ 198.70, 154.83, 141.44, 136.64, 133.39, 128.89, 128.11, 110.56, 105.41, 36.30, 22.11.

*4.4.25. 3-(naphthalen-2-yl)-1-phenylpropan-1-one (**3al**).*[4d] White solid. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 8.00 (d, *J* = 7.6 Hz, 2H), 7.83 (t, *J* = 8.8 Hz, 3H), 7.76 (s, 1H), 7.61 (s, 1H), 7.54 – 7.39 (m, 5H), 3.44 (d, *J* = 8.8 Hz, 2H), 3.12 (t, *J* = 7.4 Hz, 2H). ^{13}C NMR (101 MHz, DMSO-d_6, ppm): δ 199.09, 138.90, 136.59, 133.13, 131.61, 128.69, 127.93, 127.67, 127.43, 127.26 126.18, 125.95, 125.22, 39.30, 29.62.

*4.4.26. 1-phenylhexan-1-one (**3am**).*[5d] Colorless oil. ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ 7.96 (d, *J* = 7.6 Hz, 2H), 7.62 (t, *J* = 7.3 Hz, 1H), 7.52 (t, *J* = 7.6 Hz, 2H), 3.00 (t, *J* = 7.2 Hz, 2H), 1.67 – 1.54 (m, 2H), 1.36 – 1.25 (m, 4H), 0.87 (t, *J* = 6.4 Hz, 3H).^{13}C NMR (151 MHz, DMSO-d_6, ppm): δ 200.16, 136.89, 133.12, 128.81, 127.99, 37.99, 31.03, 23.67, 22.17, 13.99.

4.5. Hydrogen transfer between α,β-unsaturated ketone and benzylic alcohol.

Cs_2CO_3 (0.6 mmol, 195.6 mg) and toluene (1 mL) were placed in a Schlenk tube under a N_2 atmosphere. $[RuCl_2(\eta^6\text{-p-cymene})]_2$ (0.005 mmol, 3.1 mg), **L1** (0.01mmol, 2.8 mg), **2a** (1.1 mmol, 119.6 mg) and **1a** (1.0 mmol, 120 mg) were added in that order and the Schlenk tube was then closed and stirred at 120 ^{o}C for 18 h. The reaction was cooled to room temperature. 1,3,5-Trimethoxybenzene (168 mg, 1.0 mmol, internal standard) was added and the mixture was then diluted with ethyl acetate (18 mL). An aliquot of the reaction solution was further analyzed by ^{1}H NMR spectroscopy.

4.6. *In situ* monitoring of the ruthenium hybrid by ^{1}H NMR and ESI-MS.

Cs_2CO_3 (0.6 mmol, 195.6 mg) and toluene-d_8 (1 mL) were placed in a Schlenk tube under a N_2 atmosphere. $[RuCl_2(\eta^6\text{-p-cymene})]_2$ (0.025 mmol, 15.5 mg), **L1** (0.05 mmol, 14.0 mg), **2a** (1.1 mmol, 120 mg) and **1a** (1.0 mmol, 120 mg) were added in that order and the Schlenk tube was closed and stirred at 120 ^{o}C for a required time. The reaction was cooled to room temperature and 0.5 mL of the reaction solution was transferred into an NMR tube under a N_2 atmosphere for the ^{1}H NMR analysis. An aliquot of the reaction solution was diluted by methanol and analyzed by ESI-MS.

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Supplementary data

The ^{1}H and ^{13}C NMR spectra for the isolated products can be found in online version at doi:

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