## Borrowing hydrogen: a catalytic route to C–C bond formation from alcohols<sup>†</sup>

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Ruthenium complexes have been shown to perform efficient transfer hydrogenation reactions between alcohols and alkenes; in combination with an *in situ* Wittig reaction, indirect formation of C–C bonds has been achieved from alcohols.

The concept of catalytic electronic activation as a route to new C–C bond forming reactions is an attractive one since it allows the use of alcohols as substrates.<sup>1</sup> One model for this involves the indirect Wittig reaction of a temporarily oxidized alcohol (Scheme 1) to yield an alkene, which is then reduced to give the final longer chain alkane.<sup>2</sup> The key to the catalytic cycle is the borrowing of hydrogen—dehydrogenation of alcohol to aldehyde releases H<sub>2</sub>, which would be stored by the catalytic metal fragment and then returned in the final hydrogenation step. The development of catalytic systems is therefore likely to involve metal complexes in which H<sub>2</sub> dissociation and re-coordination is facile, preferably without the requirement for forcing conditions.<sup>3</sup>

Our previous attempts at achieving this reaction using an iridium-based system required heating at 150 °C for 72 h.<sup>2</sup> Herein we report on a ruthenium-catalysed approach requiring milder reaction conditions. The use of a ruthenium N-heterocyclic carbene complex allows the reaction to be carried out at significantly lower temperatures and reaction times. We have recently reported the facile C–H bond activation of the N-heterocyclic carbene 1,3-bis(2,4,6-trimethylphenyl)imidazol-2-ylidene (IMes) in Ru(I-Mes)(PPh<sub>3</sub>)<sub>2</sub>(CO)H<sub>2</sub> (1) at room temperature in the presence of a sacrificial alkene (Scheme 2).<sup>4</sup> The C–H cleavage product **2** readily



Scheme 1 Catalytic electronic activation: indirect Wittig reaction upon alcohols.



Scheme 2 Reversible dehydrogenation/hydrogenation pathway of complex 1.

† Electronic Supplementary Information (ESI) available: Experimental procedures and characterization data for compounds 1, 11, 12, 13, 15 and 17 along with general experimental procedures. See http://www.rsc.org/ suppdata/cc/b3/b312162c/ reforms the starting dihydride upon reaction with  $H_2$ . The rapid hydrogenation of alkenes<sup>5</sup> and the reversibility of the pathway illustrated in Scheme 2 prompted us to investigate the suitability of alcohols as hydrogen donors in this process.<sup>6</sup>

It was subsequently demonstrated that vinyltrimethylsilane (3) could be completely hydrogenated by complex 1 at 70 °C to provide ethyltrimethylsilane (4) with isopropanol acting as the hydrogen donor (Scheme 3). Indeed, the crossover transfer hydrogenation<sup>7</sup> reaction between one equivalent of alcohol and one equivalent of alkene could also be readily achieved (Scheme 3). ( $\pm$ )-Phenethyl alcohol (6) and *tert*-butyl cinnamate (5) were converted solely into acetophenone (8) and *tert*-butyl dihydrocinnamate (7) using 5 mol% of complex 1.

The ability to effect a crossover transfer hydrogenation is critical to the success of the indirect Wittig reaction identified in Scheme 1. In the absence of crossover hydrogenation the cycle is unable to proceed once the initial catalyst has been exhausted. Following the success of these transfer hydrogenation reactions the catalytic activity of complex 1 in the indirect Wittig process was examined (Scheme 4, Table 1). Table 1 shows the performance of complex 1 (5 mol% loading) for reaction of benzyl alcohol (9) with the ester



100 % conversion

CeDe, 50 °C, 16 h

7

Scheme 3 Transfer hydrogenation reactions with complex 1.



Scheme 4 Ruthenium catalysed indirect Wittig reactions with benzyl ester ylide 10.

Table	1 Effect	of ruthenium	catalysts	upon the	e indirect	Wittig	reaction	of
benzyl	alcohol	<b>9</b> <sup>a</sup>						

Entry	Precursor (5 mol%)	Ligand (mol%)	Conversion (%) <sup>b</sup>
1 2 3	1 Ru(PPh <sub>3</sub> ) <sub>3</sub> (CO)H <sub>2</sub> Ru(PPh <sub>3</sub> ) <sub>2</sub> (CO)H <sub>2</sub>	 IMes (5)	90 80 87
$4^c$	$Ru(PPh_3)_3(CO)H_2$	IMes (5)	86

<sup>*a*</sup> The reactions were carried out on a 0.5 mmol scale in toluene (1.5 mL) at 80 °C for 24 hours using 1.1 equivalents of ylide **10**. <sup>*b*</sup> Determined by <sup>1</sup>H NMR spectroscopy. <sup>*c*</sup> The precursor and IMes were heated at 70 °C for 1.5 hours in toluene before addition of the remaining reagents.

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5

ylide (10) in toluene solution at 80 °C. In all cases 5 mol% of vinyltrimethylsilane (3) was added to accomplish the initial dehydrogenation of the catalyst required for the reaction to proceed. The reaction catalysed by complex 1 afforded 90% of the dihydrocinnamate product (11) after 24 hours (entry 1). The complex Ru(PPh<sub>3</sub>)<sub>3</sub>(CO)H<sub>2</sub> also proved to be successful in the indirect Wittig reaction, although it proved to be inferior to complex 1 over the same reaction period (entry 2).<sup>8</sup>

The highest levels of activity of complex **1** are associated with isolated material; however *in situ* generation of the catalyst proved to be successful (entries 3 and 4). Thus, whilst the carbene complex **1** is the most successful catalyst, commercially available complex  $Ru(PPh_3)_3(CO)H_2$  was also reasonably effective.

We further demonstrated that the indirect Wittig reaction catalysed by **1** could be successfully achieved in high yield by the use of alternative phosphorane ester ylides with other alcohol substrates (Scheme 5). Using optimised reaction conditions (1 mol% **1**, 1.00 M concentration, 80 °C) the indirect Wittig adducts **11**, **12**, **13**, **15** and **17** were obtained in good to excellent isolated yields following column chromatography (70–84%). These results demonstrate that complex **1** displays high catalytic activity for C–C bond formation *via* this route at moderately low temperatures (80 °C). In contrast, the previously reported<sup>2</sup> iridium catalysed reactions afforded indirect Wittig adducts in lower yield, 47–71%, even under extremely forcing reaction conditions (150 °C, 72 hours) and at considerably higher catalyst loadings (5 mol%). In



Scheme 5 Synthesis of indirect Wittig reaction adducts (1 mol% 1, 1.1 equiv.  $Ph_3P=CHCO_2R$ , 2 mol%  $H_2C=CHSiMe_3$ , PhMe, 1.00 M, 80 °C); (a) 24 hour reaction time; (b) 48 hour reaction time.

addition, the results indicate that the presence of an N-heterocyclic carbene ligand is beneficial for improved reactivity in comparison with other complexes.

In conclusion, we have demonstrated that ruthenium complexes act as catalysts for the formation of C–C bonds from alcohol substrates *via* an intriguing indirect Wittig reaction.

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