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C−C Bond Formation via C−H Bond Activation Using an in Situ-Generated Ruthenium Catalyst

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Abstract: We report here our full results concerning the possibility of generating in situ from a stable and readily available ruthenium(II) source a highly active ruthenium catalyst for C−H bond activation. The versatility of this catalytic system has been demonstrated, as it offers the possibility of modifying the electronic and steric properties of the catalyst by fine-tuning of the ligands, allowing functionalization of various substrates. Aromatic ketones and imines could be easily functionalized by the reaction with either vinylsilanes or styrenes, depending on the electronic and steric nature of the ligand. Moreover, variable-temperature NMR experiments and the isolation of a ruthenium intermediate complex provided some insights into the generation of the active catalytic ruthenium species in this reaction.

Introduction

Transition-metal-catalyzed C−C bond-forming reactions have emerged as a powerful tool for making C−C bonds in organic synthesis, allowing access to unconventional and more elaborated structural backbones with high selectivity and efficiency. One of the most often used examples of such a reaction is certainly the Suzuki−Miyaura reaction.[1] More recently, much attention has been paid to green and sustainable reactions with the aim of developing environmentally friendly processes. Among them, catalytic processes involving C−H bond activation are highly desirable, not only because they allow the functionalization of more readily available starting materials (the atom economy concept[2]) but also because they produce clean reactions (reduced amounts of salts).[3] In the field of C−C bond formation via C−H activation, several catalytic reactions have recently been developed, mainly involving complexes of low-valent transition metals such as palladium, rhodium, and ruthenium, which have been extensively developed in that field.[3]

Among these catalytic processes,[4] hydroarylation reactions catalyzed by transition metals allow the functionalization of alkenes with a 100% atom economy.[3,5] In such reactions, low-valent ruthenium complexes with Ru oxidation states of 0 or II [e.g., Ru(cod)(cot), $Ru_3(CO)_{12}$, $RuH_2(PPh_3)_4$, and $RuH_2(CO)(PPh_3)_3$] have proven their efficiency because of their high

(1) (a) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457. (b) Kotha, S.; Lahiri, K.; Kashinath, D. *Tetrahedron* **2002**, *58*, 9633. (c) Nicolaou, K. C.; Bulger, P. G.; Sarlah, D. *Angew. Chem., Int. Ed.* **2005**, *44*, 4442. (d) Zapf, A.; Beller, M. *Chem. Commun.* **2005**, 431. (e) Miyaura, N. *Bull. Chem. Soc. Jpn.* **2008**, *81*, 1535. (f) Martin, R.; Buchwald, S. L. *Acc. Chem. Res.* **2008**, *41*, 1461.

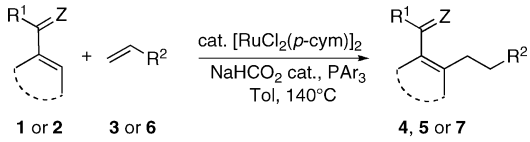
(2) (a) Trost, B. M. *Science* **1991**, *254*, 1471. (b) Trost, B. M. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 259. (c) Trost, B. M. *Acc. Chem. Res.* **2002**, *35*, 695. (d) Eissen, M.; Mazur, R.; Quebbemann, H. G.; Pennemann, K. H. *Helv. Chim. Acta* **2004**, *87*, 524.

(3) For reviews, see: (a) Shilov, A. E.; Shul'pin, G. B. *Chem. Rev.* **1997**, *97*, 2879. (b) Dyker, G. *Angew. Chem., Int. Ed.* **1999**, *38*, 1698. (c) Guari, Y.; Sabo-Etienne, S.; Chaudret, B. *Eur. J. Inorg. Chem.* **1999**, 1047. (d) Jia, C.; Kitamura, T.; Fujiwara, Y. *Acc. Chem. Res.* **2001**, *34*, 633. (e) Ritleng, V.; Sirlin, C.; Pfeffer, M. *Chem. Rev.* **2002**, *102*, 1731. (f) Kakiuchi, F.; Chatani, N. *Adv. Synth. Catal.* **2003**, *345*, 1077. (g) Dick, A. R.; Sanford, M. S. *Tetrahedron* **2006**, *62*, 2439. (h) Herrerías, C. I.; Yao, X.; Li, Z.; Li, C. J. *Chem. Rev.* **2007**, *107*, 2546. (i) Campeau, L. C.; Stuart, D. R.; Fagnou, K. *Aldrichimica Acta* **2007**, *40*, 35. (j) Park, Y. J.; Park, J. W.; Jun, C. H. *Acc. Chem. Res.* **2008**, *41*, 222. (k) Kakiuchi, F. *Top. Organomet. Chem.* **2008**, *24*, 1. (l) Li, B. J.; Yang, S. D.; Shi, Z. J. *Synlett* **2008**, 949. (m) Mori, A.; Sugie, A. *Bull. Chem. Soc. Jpn.* **2008**, *81*, 548. (n) Kakiuchi, F.; Kochi, T. *Synthesis* **2008**, 3013.

(4) For some recent examples of coupling reactions involving C−H bond activation, see: (a) Kakiuchi, F.; Kan, S.; Igi, K.; Chatani, N.; Murai, S. *J. Am. Chem. Soc.* **2003**, *125*, 1698. (b) Kakiuchi, F.; Matsuura, Y.; Kan, S.; Chatani, N. *J. Am. Chem. Soc.* **2005**, *127*, 5936. (c) Stuart, D. R.; Fagnou, K. *Science* **2007**, *316*, 1172. (d) Yang, S. D.; Sun, C. L.; Fang, Z.; Li, B. J.; Li, Y. Z.; Shi, Z. J. *Angew. Chem., Int. Ed.* **2008**, *47*, 1473. (e) Wang, D. H.; Wasa, M.; Giri, R.; Yu, J. Q. *J. Am. Chem. Soc.* **2008**, *130*, 7190. (f) Zhao, X.; Yu, Z. *J. Am. Chem. Soc.* **2008**, *130*, 8136. (g) Shi, B. F.; Maugel, N.; Zhang, Y. H.; Yu, J. Q. *Angew. Chem., Int. Ed.* **2008**, *47*, 4882. (h) Ackermann, L.; Althammer, A.; Born, R. *Tetrahedron* **2008**, *64*, 6115. (i) Deng, G.; Zhao, L.; Li, C. J. *Angew. Chem., Int. Ed.* **2008**, *47*, 6278. (j) Cho, S. H.; Hwang, S. J.; Chang, S. *J. Am. Chem. Soc.* **2008**, *130*, 9254. (k) Ban, I.; Sudo, T.; Taniguchi, T.; Itami, K. *Org. Lett.* **2008**, *10*, 3607. (l) Özdemir, I.; Demir, S.; Çetinkaya, B.; Gourlaouen, C.; Maseras, F.; Bruneau, C.; Dixneuf, P. H. *J. Am. Chem. Soc.* **2008**, *130*, 1156. (m) Chaumontet, M.; Piccardi, R.; Baudoin, O. *Angew. Chem., Int. Ed.* **2009**, *48*, 179. (n) Campeau, L. C.; Stuart, D. R.; Leclerc, J.; Bertrand-Laperle, M.; Villemure, E.; Sun, H.; Lasserre, S.; Guimond, N.; Lecavallier, M.; Fagnou, K. *J. Am. Chem. Soc.* **2009**, *131*, 3291.

(5) For some recent hydroalkylation reactions, see: (a) Grutters, M. M. P.; Müller, C.; Vogt, D. *J. Am. Chem. Soc.* **2006**, *128*, 7414. (b) Nishimura, T.; Guo, X. X.; Ohnishi, K.; Hayashi, T. *Adv. Synth. Catal.* **2007**, *349*, 2669. (c) Tsai, A. S.; Bergman, R. G.; Ellman, J. A. *J. Am. Chem. Soc.* **2008**, *130*, 6316. (d) Kuninobu, Y.; Kikuchi, K.; Tokunaga, Y.; Nishina, Y.; Takai, K. *Tetrahedron* **2008**, *64*, 5974. (e) McKeown, B. A.; Foley, N. A.; Lee, J. P.; Gunnoe, T. B. *Organometallics* **2008**, *27*, 4031. (f) Harada, H.; Thalji, R. K.; Bergman, R. G.; Ellman, J. A. *J. Org. Chem.* **2008**, *73*, 6772. (g) Kozhushkov, S. I.; Yufit, D. S.; Ackermann, L. *Org. Lett.* **2008**, *10*, 3409. (h) Nakao, Y.; Kashihara, N.; Kanyiva, K. S.; Hiyama, T. *J. Am. Chem. Soc.* **2008**, *130*, 16170. (i) Luedtke, A. T.; Goldberg, K. I. *Angew. Chem., Int. Ed.* **2008**, *47*, 7694. (j) Vasylyev, M.; Alper, H. *Angew. Chem., Int. Ed.* **2009**, *48*, 1287. (k) Kubiak, R.; Prochnow, I.; Doye, S. *Angew. Chem., Int. Ed.* **2009**, *48*, 1153.

Scheme 1. C−C Bond Formation via C−H Bond Activation Using an in Situ-Generated Ruthenium Catalyst



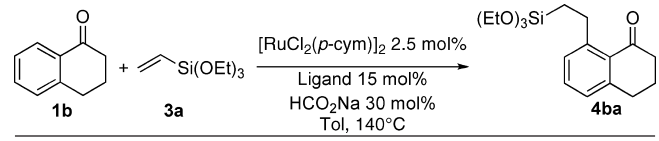
Z = O (**1**), N*t*-Bu (**2**)
R^1 = H or alkyl
R^2 = SiR_3 (**3**), Ar (**6**)

activity in both stoichiometric and catalytic reactions.[6] However, these low-valent catalyst precursors present some drawbacks because they are generally air- and moisture-sensitive and must be stored under an inert atmosphere at low temperature in order to prevent their decomposition. Moreover, their synthesis is generally not obvious and requires several preparative and purification steps starting from commercially available $RuCl_3$. Furthermore, their preparative methods do not allow the complexation of a large variety of ligands, resulting generally in a limited scope. Indeed, in situ generation of low-valent active ruthenium species under mild conditions would be a highly desirable improvement in terms of simplicity, flexibility, and scope of the catalytic system.

We recently reported a highly efficient catalytic system that was generated in situ from a readily available ruthenium(II) source and allowed either hydroarylation of vinylsilanes (the Murai reaction),[7,8] anti-Markovnikov hydroarylation of styrenes,[9] or formation of functionalized allysilanes via C−H bond activation.[10] The catalytically active ruthenium species was generated in situ from the reaction of inexpensive $[RuCl_2(p\text{-cym})]_2$ (*p*-cym = *p*-cymene) and sodium formate, in association with a phosphane ligand. Interest in this system arises from not only the use of a stable, commercially available ruthenium source but also its flexibility, as it allowed the in situ complexation of any type of ligand to the ruthenium center, making it possible to tune the electronic and steric properties of the catalyst.

Here we report our full results concerning the functionalization of aromatic ketones via C−H bond activation and the extension of the reaction to the activation of aromatic aldimines (Scheme 1). Moreover, variable-temperature NMR experiments and the isolation of a ruthenium complex intermediate provide some insights into the generation of the active catalytic ruthenium species in this reaction.

Table 1. Ligand Screening in the Ruthenium-Catalyzed Hydroarylation of **3a** with **1b**[a]



entry	ligand	conv. after 21 h[b]
1	none	0
2	PPh_3	100[c]
3	P(*p*-tolyl)$_3$	94
4	P(*m*-tolyl)$_3$	100[c]
5	P(*o*-tolyl)$_3$	0
6	P(4-$CF_3C_6H_4$)$_3$	93[c]
7	P(4-$MeOC_6H_4$)$_3$	94
8	P(2-furyl)$_3$	55
9	$CyPPh_2$	62
10	Cy_2PPh	8
11	PCy_3	5
12	$P(OEt)_3$	0
13	$P(OPh)_3$	0
14	dppe	0
15	dppf	0
16	Binap	0

[a] Reactions were conducted using 1 mmol of **1b**, 2 equiv of **3a**, 2.5 mol % $[RuCl_2(p\text{-cym})]_2$, 3 or 1 equiv (with respect to Ru) of monodentate or bidentate ligand, respectively, and 30 mol % Na HCO_2 in toluene at 140 °C. [b] Conversion was determined by GC using an internal standard. [c] Identical conversion was obtained in less than 3 h.

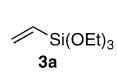
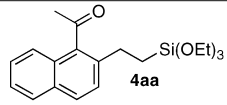
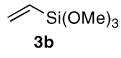
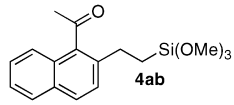
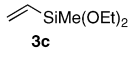
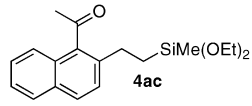
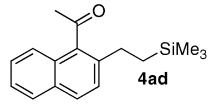
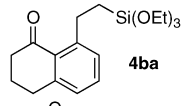
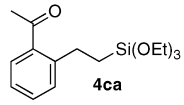
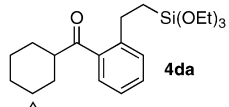
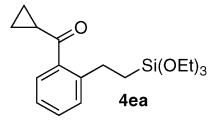
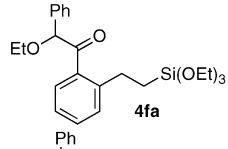
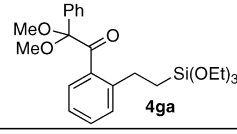
Results and Discussion

Activation of Aromatic Ketones. As reported previously, the ruthenium catalyst generated in situ from the reaction of $[RuCl_2(p\text{-cym})]_2$ and sodium formate in the presence of 3 equiv of triphenylphosphane allowed the regioselective alkylation of aromatic ketones at the ortho position of the keto substituent using vinylsilanes.[7] The electronic and steric properties of the ligand were studied and shown to greatly influence the reactivity and the yields of the alkylated ketones formed (Table 1). Although bidentate phosphane and phosphite ligands proved to be totally ineffective (entries 14−16), aromatic monophosphane ligands were very well suited to the reaction (entries 1−12). These results suggest that at least one intermediate in the catalytic cycle should have a trans configuration for the phosphane ligand, which is impossible with bidentate ligands. It is also important to note that steric hindrance on the phosphane ligand has a great influence on the course of the reaction (decreasing reactivity with increasing cone angle):[11] tri(*o*-tolyl)phosphane (entry 5) did not allow the formation of the expected adduct, whereas quantitative conversion was achieved using the meta and para isomers (entries 3 and 4) under identical conditions. The electronic nature of the ligand also greatly influences the kinetic course of the reaction, as electron-donating substituents retarded the coupling (entries 6 and 7). Indeed, from these results it appeared that electron-poor, nonhindered tri(aryl)phosphane ligands are the most suitable for this reaction. Overall, triphenylphosphane was found to be the best-adapted ligand in terms of reactivity and cost.[7]

These conditions proved to be quite general, and 1-acetonaphthone (**1a**) was efficiently alkylated by various vinylsilanes

(6) (a) Bennett, M. A.; Matheson, T. W. In *Comprehensive Organometallic Chemistry*; Wilkinson, G., Stone, F. G. A., Abel, E. W., Eds.; Pergamon Press: Oxford, U.K, 1982; Vol. 4, p 931. (b) Shriver, D. F.; Bruce, M. I. In *Comprehensive Organometallic Chemistry*; Abel, E. W., Stone, F. G. A., Wilkinson, G., Eds.; Pergamon Press: Oxford, U.K, 1995; Vol. 7. (c) Naota, T.; Takaya, H.; Murahashi, S. I. *Chem. Rev.* **1998**, *98*, 2599. (d) Mitsudo, T.; Kondo, T. *Synlett* **2001**, 309. (e) Trost, B. M.; Toste, F. D.; Pinkerton, A. B. *Chem. Rev.* **2001**, *101*, 2067. (f) *Ruthenium in Organic Synthesis*; Murahashi, S.-I., Ed.; Wiley-VCH: Weinheim, Germany, 2004. (g) Trost, B. M.; Frederiksen, M. U.; Rudd, M. T. *Angew. Chem., Int. Ed.* **2005**, *44*, 6630.
(7) Martinez, R.; Chevalier, R.; Darses, S.; Genet, J. P. *Angew. Chem., Int. Ed.* **2006**, *45*, 8232.
(8) For ruthenium-catalyzed hydroarylation processes (Murai reaction), see: (a) Murai, S.; Kakiuchi, F.; Sekine, S.; Tanaka, Y.; Kamatani, A.; Sonoda, M.; Chatani, N. *Nature* **1993**, *366*, 529. (b) Kakiuchi, F.; Sekine, S.; Tanaka, Y.; Kamatani, A.; Sonoda, M.; Chatani, N.; Murai, S. *Bull. Chem. Soc. Jpn.* **1995**, *68*, 62. (c) Sonoda, M.; Kakiuchi, F.; Chatani, N.; Murai, S. *Bull. Chem. Soc. Jpn.* **1997**, *70*, 3117. (d) Murai, S.; Chatani, N.; Kakiuchi, F. *Pure Appl. Chem.* **1997**, *69*, 589. (e) Fujii, N.; Kakiuchi, F.; Yamada, A.; Chatani, N.; Murai, S. *Bull. Chem. Soc. Jpn.* **1998**, *71*, 285. (f) Kakiuchi, F.; Murai, S. *Acc. Chem. Res.* **2002**, *35*, 826.
(9) Martinez, R.; Genet, J. P.; Darses, S. *Chem. Commun.* **2008**, 3855.
(10) Simon, M.; Martinez, R.; Genêt, J.; Darses, S. *Adv. Synth. Catal.* **2009**, *351*, 153.
(11) Tolman, C. A. *Chem. Rev.* **1977**, *77*, 313.

Table 2. Compatible Vinylsilanes and Keto Substituents in the Ruthenium-Catalyzed C−C Bond Formation Reaction[a]

Entry	Alkene	Time (h)	Product	Yield[b]
1	 **3a**	0.3	 **4aa**	100
2	 **3b**	1	 **4ab**	100[c]
3	 **3c**	20	 **4ac**	89
4	 **3d**	5	 **4ad**	97
5	**3a**	1	 **4ba**	95
6	**3a**	1	 **4ca**	100 (100/0)
7	**3a**	1	 **4da**	100 (100/0)
8	**3a**	20	 **4ea**	Traces[c]
9	**3a**	20	 **4fa**	21 (100/0)
10	**3a**	20	 **4ga**	81[c] (90/10)

[a] Reactions were conducted using 1 mmol of ketone **1**, 2 equiv of vinylsilane **3**, 2.5 mol % $[RuCl_2(p\text{-cym})]_2$, 15 mol % PPh_3, and 30 mol % $NaHCO_2$ in toluene at 140 °C. [b] Isolated yields of mono- and disubstituted adducts; ratios of mono- to disubstituted adduct are given in parentheses. [c] Conversion was determined by GC using an internal standard.

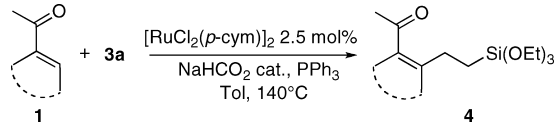
in the presence of 5 mol % ruthenium catalyst in toluene at 140 °C (Table 2, entries 1−4). Good yields were generally obtained, but the reaction times depended on the substituents on the silicon reagent. The reactions with triethoxyvinylsilane (**3a**) or trimethoxyvinylsilane (**3b**) finished in less than 1 h (entries 1 and 2), while the hydroarylations using diethoxymethylvinylsilane and trimethylvinylsilane were slower (entries 3 and 4), showing that trialkoxyvinylsilanes seem to be more reactive. We do not actually know the reason for the higher reactivity of alkoxyvinylsilanes than alkylvinylsilanes, but studies are underway to quantify these electronic effects.

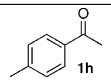
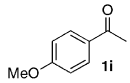
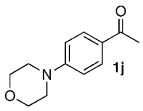
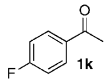
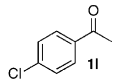
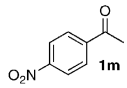
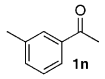
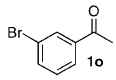
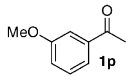
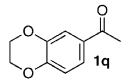
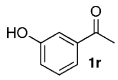
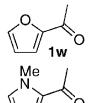
We also evaluated the influence of different acyl directing groups on the reactivity (Table 2, entries 5−10). The hydroarylation of triethoxyvinylsilane (**3a**) by ketones bearing aliphatic functionalities occurred readily and led to quantitative yields (entries 5−7) except in the case of cyclopropyl-substituted ketone **1e** (entry 8). The latter is probably much more fragile, leading to generation of many byproducts during the reaction. It also seems that the steric bulk of the acetyl group did not influence the reactivity (entries 6−7). With ethoxybenzyl-substituted ketone **1f**, the conversion decreased sharply (entry 9). This poor reactivity can be rationalized in terms of the presence of an acidic hydrogen that may react with the low-valent ruthenium complex. This hypothesis was partially confirmed by the fact that when the reaction was carried out with substrate **1g**, which is similar but lacks the benzylic hydrogen, a conversion of 81% was observed (entry 10).

These preliminary results show that the ketones that can be functionalized in the presence of the in situ-generated catalytic system are relatively varied. We then examined the tolerance of our catalytic system toward substituents on the aromatic ring (Table 3). With para-substituted aromatic ketones, the reaction occurred readily and generally gave very good yields. For example, the reaction of 4-methylacetophenone (**1h**) with triethoxyvinylsilane (**3a**) was quantitative (entry 1). The electronic nature of the substituents did not appear to strongly influence the reactivity. Indeed, methoxy, morpholino, and fluoro substituents led to yields ranging from 80 to 100% with comparable reaction times (entries 2−4). However, it should be noted that the conversion was slightly lower with 4-chloroacetophenone (**1l**, entry 5), certainly as a result of oxidative addition of ruthenium(0) in the C−Cl bond to generate an inactive ruthenium complex. Finally, the presence of a nitro group completely inhibited the catalytic activity (entry 6). In most of the examined reactions with para-substituted acetophenones, disubstitution adducts were also formed, leading to mixtures of mono- and disubstituted products. The proportion of these products varied with the substitution of the acetophenone and the reaction time: the monosubstituted product was formed predominantly with methyl and methoxy substituents (entries 1 and 2) while the proportion of disubstituted product was much more important with other substrates. Indeed, the electronic properties of the substituents seemed to have an influence on the selectivity of the reaction, but this effect is actually rather difficult to rationalize since similar results were obtained for an electron-donating group (morpholino, entry 3) and an electron-withdrawing group (fluorine, entry 4). In the literature, it has been reported that the presence of electron-donating substituents favors the disubstituted adduct by enhancing the complexation of the carbonyl group, thereby favoring the activation of the second C−H bond.[8c]

In the case of meta-substituted acetophenones, the two ortho positions of the acetyl group are not equivalent, and two isomers may be obtained depending on the regioselectivity of the activation (Table 3, entries 7−11). With acetophenones substituted with methyl or bromine, activation occurred at the least hindered position (entries 7, 8). In contrast, the presence of an oxygenated substituent favored a reversal of the regioselectivity (entries 9, 10). Under identical conditions, 3-hydroxyacetophenone (**1r**) failed to react with triethoxyvinylsilane (entry 11). Indeed, the activation process occurs at the less hindered position except in the presence of a potential complexing substituent. Similar regioselectivity was observed using the $RuH_2(CO)(PPh_3)_3$ complex[8c] and in the anti-Markovnikov hydroarylation of styrenes,[9] suggesting that a second complexation on the oxygen meta to ruthenium could direct the activation to the most congested side. However these results can also be explained by a greater stabilization of the oxidative-addition intermediate, as the oxidation addition is a reversible process.

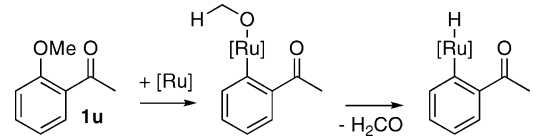
Table 3. Ruthenium-Catalyzed Hydroarylation of Vinylsilanes by Aromatic Ketones[a]



Entry	Ketone	Time	Yield[b]	Mono/di[c]
1	 1h	1	100 (**4ha**)	85/15
2	 1i	0.5	100 (**4ia**)	75/25
3	 1j	3	80 (**4ja**)	46/54
4	 1k	2	92 (**4ka**)	50/50
5	 1l	2	64 (**4la**)	59/41
6	 1m	20	0	-
7	 1n	20	83 (**4na**)	94/6[d]
8	 1o	20	70 (**4oa**)	86/14[d]
9	 1p	1	100 (**4pa**)	12/88[d]
10	 1q	1,5	99[e] (**4qa**)	0/100[d]
11	 1r	20	0	-
12	 1s	20	59 (**4sa**)	
13	 1t	20	0	
14	 1u	60	20[f] (**4ua**)	
15	 1v	2	100 (**4va**)	
16	 1w	4	85 (**4wa**)	
17	 1x	6	(2)	
18	 1y	4	(4)	

[a] Reactions were conducted using 1 mmol of ketone **1**, 2 equiv of **3a**, 2.5 mol % $[RuCl_2(p\text{-cym})]_2$, 15 mol % PPh_3, and 30 mol % $NaHCO_2$ in toluene at 140 °C. [b] Isolated yields of mono- and disubstituted adducts. Values in parentheses are conversions determined by GC using an internal standard. [c] Ratios of mono- to disubstituted adduct. [d] Selectivity for 6- and 2-substituted products. [e] Using 3 equiv of triethoxyvinylsilane. [f] Formation of 25% **4ca**.

Scheme 2. Oxidative Addition of Ruthenium in the C−OMe Bond Followed by β-Elimination



The two effects (complexation and steric hindrance) are competitive, and in the case of 3-bromoacetophenone (**1o**, entry 8), the lower regioselectivity relative to 3-methylacetophenone (**1n**, entry 7) may be explained by some complexation of the bromine atom with the ruthenium center.

The presence of substituents at the position ortho to the acetyl group led to an overall decrease in the hydroarylation yield (Table 3, entries 12−14). The moderate conversion and yield obtained with 2-methylacetophenone (entry 12) is surprising since quantitative yields have been observed using the $RuH_2(CO)(PPh_3)_3$ complex.[8c] In the presence of halogens in the ortho position, no conversion was observed (entry 13), and GC−MS analysis of the reaction mixture showed the formation of acetophenone (**1c**) resulting from dehalogenation of **1t**. The absence of catalytic activity with this substrate is probably due to the oxidative addition of ruthenium(0) into the C−X bond to generate an inactive aryl(halogeno)ruthenium complex. A similar phenomenon (oxidative addition) was observed in the reaction with 2-methoxyacetophenone (entry 14), but in this case, after the ruthenium was inserted into the C−O bond, a β-hydride elimination could occur, generating an aryl(hydrido)-ruthenium that led to byproduct **4ca**, identical to the reaction with acetophenones (Scheme 2). Indeed, in the latter case, the activity of the catalyst was not completely lost.[8c,12]

The activity of heteroaromatic ketones was also evaluated in the reaction with triethoxyvinylsilane (Table 3, entries 15−18). It appeared that only 2-acetylthiophene (**1v**) and 2-acetylfuran (**1w**) could be functionalized with good yields (entries 15 and 16). The presence of a nitrogen atom on the aromatic ring resulted in a loss of catalytic activity, and no product formation was observed (entries 18 and 19).

During the optimization studies of the hydroarylation of vinylsilanes, it appeared that the reaction could be performed in the absence of solvent with identical yields using the same catalyst loading (5 mol %). Conducting reactions in the absence of solvent becomes particularly interesting when scaling up the reactions, as it avoids the use of large, pressurized reactors. In the absence of solvent, we were able to achieve hydroarylation of trimethoxyvinylsilane (**3b**) with 1-acetonapthone (**1a**) at lower catalyst loading (Scheme 3). Thus, in the presence of 0.04 mol % ruthenium(II) dimer, 0.12 mol % PPh_3, and 0.24 mol % sodium formate, a conversion of 45% (on a 50 mmol scale) was achieved after 120 h reaction, corresponding to a turnover number (TON) of 1125, which is higher than those described in the literature for similar processes involving C−H bond activation.[3]

Activation of Aromatic Aldimines. Having at our disposal a flexible and efficient catalytic system, we envisaged extending its scope to aromatic substrates bearing other ortho-directing

(12) For some examples of ruthenium-catalyzed coupling reactions involving C−heteroatom activation, see: (a) Kakiuchi, F.; Usui, M.; Ueno, S.; Chatani, N.; Murai, S. *J. Am. Chem. Soc.* **2004**, *126*, 2706. (b) Ueno, S.; Mizushima, E.; Chatani, N.; Kakiuchi, F. *J. Am. Chem. Soc.* **2006**, *128*, 16516. (c) Ueno, S.; Chatani, N.; Kakiuchi, F. *J. Am. Chem. Soc.* **2007**, *129*, 6098.

Scheme 3. C−C Bond Formation via C−H Bond Activation under Solvent-Free and Low Catalyst Loading Conditions

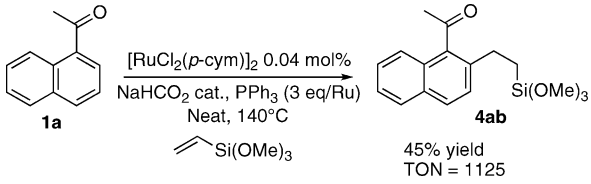
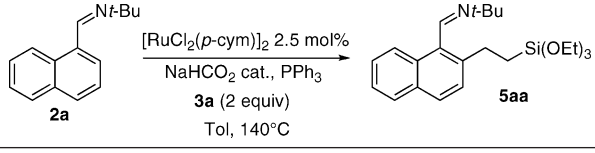


Table 4. Influence of the Amount of PPh_3 Ligand (*n*) in the Reaction of Aldimines with Vinylsilanes[a]



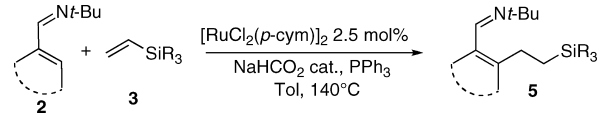
entry	*n* (equiv/Ru)	time (h)	conv. (%)[b]
1	3	20	100
2	2	20	100
3	1	1	100 (99)
4	0	20	100

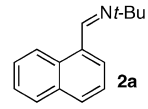
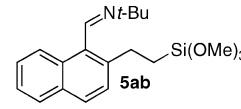
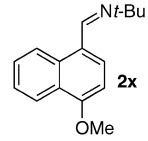
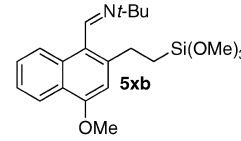
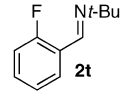
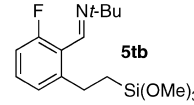
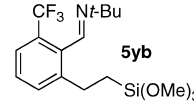
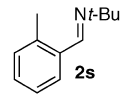
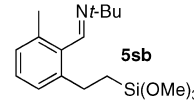
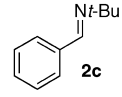
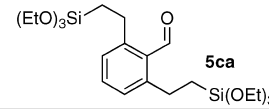
[a] Reactions were conducted using 1 mmol of imine **2a**, 2 equiv of vinylsilane **3a**, 2.5 mol % $[RuCl_2(p\text{-cym})]_2$, 30 mol % $NaHCO_2$, and *n* equiv of PPh_3 (relative to Ru) in toluene at 140 °C. [b] Conversions were determined by GC; isolated yields after hydrolysis of the imine are given in parentheses.

substituents. The C−H bond activation at the ortho position of aromatic aldimines has been described by Murai and co-workers, and under identical conditions, the catalyst precursor $RuH_2(CO)(PPh_3)_3$ showed low activity while the ruthenium cluster $Ru_3(CO)_{12}$ was more active.[13,14] The results obtained with the $Ru_3(CO)_{12}$ cluster, which bears no phosphane ligand, led us to study the influence of the amount of phosphane relative to ruthenium in the reaction between *N-tert*-butyl-1-naphthaldimine (**2a**) and triethoxyvinylsilane (**3a**) (Table 4). Under the previously optimized conditions and using 2 or 3 equiv of PPh_3 relative to ruthenium, C−H bond functionalization at the ortho position of the imine occurred with quantitative conversion, but the reaction was slower than those with aromatic ketones (entries 1−2). In the absence of triphenylphosphane, the reaction was also slow, but this result shows that the phosphane ligand was no longer necessary and that the imine could act as a ligand to the ruthenium (entry 4). However, the use of 1 equiv of PPh_3 relative to ruthenium greatly accelerated the reaction rate (entry 3) and led to the isolation of the hydroarylation product of triethoxyvinylsilane as the aldehyde in 99% yield after hydrolysis.

These conditions for the activation of *N-tert*-butyl-1-naphthaldimine were applied to the functionalization of other aldimines, particularly ortho-substituted ones (Table 5), as these imines have been described as the only reactive ones in the presence of ruthenium complexes.[13a] Naphthaldimine derivatives reacted with trimethoxyvinylsilane (**3b**) to afford hydroarylation products with quantitative conversions (entries 1 and 2). Under

Table 5. Ruthenium-Catalyzed Functionalization of Aldimines[a]



Entry	Aldimine **2**	Product **5**	Yield (%)[b]
1	 **2a**	 **5ab**	89 (100)
2	 **2x**	 **5xb**	42 (100)
3	 **2t**	 **5tb**	78 (91)
4	 **2y**	 **5yb**	62 (100)
5	 **2s**	 **5sb**	(21)
6	 **2c**	 **5ca**	50[c] (66)

[a] Reactions were conducted using 1 mmol of imine **2**, 2 equiv of vinylsilane **3**, 2.5 mol % $[RuCl_2(p\text{-cym})]_2$, 30 mol % $NaHCO_2$, and 5 mol % PPh_3 in toluene at 140 °C. [b] Isolated yields of products obtained by bulb-to-bulb distillation; conversions determined by GC are given in parentheses. [c] Isolated as the disubstituted aldehyde.

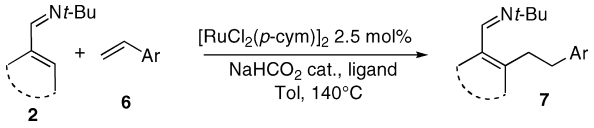
the same conditions, good conversions and yields were also achieved with *N-tert*-butylbenzaldimine derivatives substituted with a fluorine or a trifluoromethyl group at the ortho position (entries 3 and 4). The good reactivity of the *N-tert*-butyl-2-fluorobenzaldimine (**2t**, entry 3) is all the more remarkable in that, by comparison, the 2-fluoroacetophenone was not active using the catalytic system generated in situ (Table 2, entry 13). The moderate yields (compared with conversion) that were generally obtained can be explained by the fact that the products were isolated in the form of imines by bulb-to-bulb distillation on a small reaction scale to avoid the hydrolysis of imine and trimethoxysilyl groups. As observed for 2-methylacetophenone (**4s**, Table 2, entry 12), the presence of a methyl group in the ortho position appeared to decrease the activity of the catalyst (entry 5). The results in terms of conversion and selectivity are in general higher than those described in the literature for the use of $Ru_3(CO)_{12}$ as the catalyst precursor,[13a] and the product of oxidative coupling between the aromatic imine and the olefin was not observed using the present catalytic system. Under these conditions, it also appeared that non-ortho-substituted imines were also reactive, as the alkylation of **2c** provided disubstituted aldehyde **5ca** in a moderate 50% yield (entry 6).

The reaction is not limited to the hydroarylation of vinylsilanes, and under the previously described conditions,[9] anti-Markovnikov hydroarylation of styrenes could be achieved using *N-tert*-butylaldimines (Table 6). Indeed, the use of 1 equiv of $PhPCy_2$ relative to ruthenium allowed the functionalization of

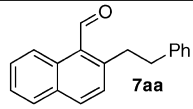
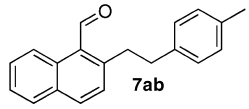
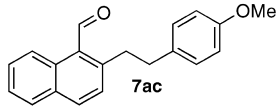
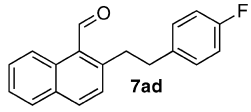
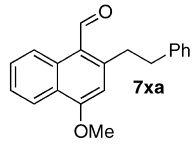
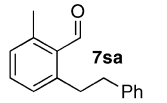
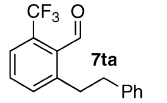
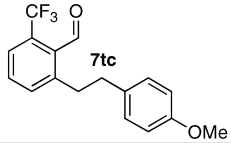
(13) (a) Kakiuchi, F.; Yamauchi, M.; Chatani, N.; Murai, S. *Chem. Lett.* **1996**, *25*, 111. (b) Berger, D.; Göbel, A.; Imhof, W. *J. Mol. Catal. A* **2001**, *165*, 37. (c) Chatani, N.; Kamitani, A.; Murai, S. *J. Org. Chem.* **2002**, *67*, 7014.

(14) For example of imines activation involving other transition metal catalysis, see ref 5d and: (a) Jun, C. H.; Hong, J. B.; Kim, Y. H.; Chung, K. Y. *Angew. Chem., Int. Ed.* **2000**, *39*, 3440. (b) Colby, D. A.; Bergman, R. G.; Ellman, J. A. *J. Am. Chem. Soc.* **2008**, *130*, 3645. (c) Harada, H.; Thalji, R. K.; Bergman, R. G.; Ellman, J. A. *J. Org. Chem.* **2008**, *73*, 6772, and references cited therein.

Table 6. Ruthenium-Catalyzed Hydroarylation of Styrenes by Aldimines[a]



2 6 7

Entry	Ar	Product	Yield[b]
1	Ph (**6a**)	 **7aa**	75
2	4-MeC$_6$H$_4$ (**6b**)	 **7ab**	52
3	4-MeOC$_6$H$_4$ (**6c**)	 **7ac**	68
4	4-FC$_6$H$_4$ (**6d**)	 **7ad**	62
5	**6a**	 **7xa**	52
6	**6a**	 **7sa**	Traces[c]
7	**6a**	 **7ta**	82[c,d]
8	**6c**	 **7tc**	55[c,e]

[a] Reactions were conducted using 1 mmol of aldimine **2**, 3 or 4 equiv of styrene **6**, 2.5 mol % [RuCl$_2$(*p*-cym)]$_2$, 30 mol % NaHCO$_2$, and 5 mol % PCy$_2$Ph in toluene at 140 °C. [b] Isolated yield after 48 h of reaction; the anti-Markovnikov adduct was obtained with more than 99% selectivity. [c] Using (4-CF$_3$C$_6$H$_4$)$_3$P (5 mol %) as the ligand. [d] Including 27% Heck-type product. [e] Including 33% Heck-type product.

naphthaldimines (entries 1−5), as observed in the case of acetonaphthones.[9] Whatever the substitution present in the styrene moiety, the hydroarylation by naphthaldimines resulted in the formation of the expected product with total anti-Markovnikov regioselectivity; this selectivity was higher than that observed with 1-acetonaphthone and can be explained by steric congestion linked to the presence of the *tert*-butyl group. Quite good yields of substituted aldehydes were uniformly obtained after hydrolysis over SiO$_2$. Substituted naphthaldimine **2x** also underwent the alkylation by styrene **6a** in moderate yield.

C−H bond functionalization of aldimines derived from ortho-substituted benzaldehydes was best achieved using (4-CF$_3$C$_6$H$_4$)$_3$P as the ligand (Table 6, entries 6−8), and using this ligand afforded only the anti-Markovnikov adducts.[9] However, in this reaction, formation of some Heck-type product was also observed, and the reaction with methyl-substituted aldimine **2s** yielded only traces of product. It is important to note that very low conversions were achieved in the case of aromatic aldimines bearing no substituent at the ortho position. Overall, this methodology is all the more interesting in that it is complementary to the Friedel−Crafts reaction, which leads to Markovnikov selectivities and reversed regioselectivities.

Indeed, this in situ-generated ruthenium catalyst allows the functionalization of various substrates by fine-tuning of either the electronic or steric properties of the phosphane ligand around the ruthenium center. Moreover, the reaction is operationally simple and uses a relatively cheap ruthenium source and reagents.

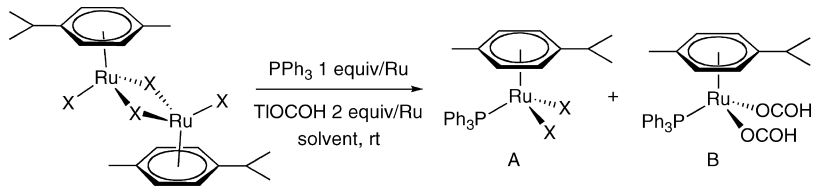
Formation of the Active Ruthenium Species. In order to better understand the formation of the active ruthenium species generated in situ, we studied the reaction between formate salts and the ruthenium(II) precursor, [RuCl$_2$(*p*-cym)]$_2$. These studies were conducted by monitoring the generation and evolution of the various ruthenium species using both ^{1}H and ^{31}P NMR as well as by the isolation of an intermediate complex.

In a first trial to study the evolution of the ruthenium(II) precursor in the presence of formate salts, we envisioned the reaction between the dimer [RuI$_2$(*p*-cym)]$_2$[15] in the presence of 1 equiv of triphenylphosphane and 2 equiv of thallium formate relative to ruthenium in benzene-d_6; the iodo precursor was chosen in the hope of favoring the ligand exchange.[16] After 5 h of reaction at room temperature, the ^{31}P NMR spectrum revealed the complete disappearance of triphenylphosphane ($\delta = -5.2$ ppm) and the presence of two new signals at 21.4 and 41.7 ppm. The first of these ($\delta = 21.4$ ppm) was attributed to the known complex [RuI$_2$(*p*-cym)PPh$_3$] (**A**), which is formed by the reaction of [RuI$_2$(*p*-cym)]$_2$ with 1 equiv of triphenylphosphane (Scheme 4).[17] The second signal ($\delta = 41.7$ ppm) corresponded to another ruthenium complex, **B**, having one or more equivalents of triphenylphosphane ligands. ^{1}H NMR analysis of the reaction mixture also revealed the formation of two complexes bearing a *p*-cymene ligand. The first one was complex **A** ($\delta = 4.97$ and 4.52 ppm, $J = 6.0$ Hz for aromatics). The second one presented two doublets for the aromatic *p*-cymene that integrated to four protons ($\delta = 6.33$ and 5.15 ppm, $J = 5.9$ Hz) along with two additional signals having close chemical shifts that integrated to two protons ($\delta = 8.20$ and 8.19 ppm), which could be due to formate ligands. This second species was linked to the $\delta = 41.7$ ppm signal in the ^{31}P NMR spectrum and corresponded to complex **B**, [Ru(OCOH)$_2$PPh$_3$(*p*-cym)], as confirmed later (see below).

The addition of excess thallium formate at room temperature did not allow the quantitative formation of diformatoruthenium complex **B**, and after a prolonged time, an exchange between the *p*-cymene ligand and benzene-d_6[18] led to the complex [RuI$_2$(benzene-d_6)PPh$_3$] ($\delta = 25.2$ ppm in the ^{31}P NMR spectrum). In order to accelerate the exchange between the iodide ligand and formate, other solvents were evaluated. It

(15) (a) Carmona, D.; Ferrer, J.; Reyes, J.; Oro, L. A. *Organometallics* **1993**, *12*, 4241. (b) Neels, A.; Stoeckli-Evans, H.; Plasseraud, L.; Fidalgo, E. G.; Süss-Fink, G. *Acta Crystallogr.* **1999**, *C55*, 2030.
(16) For examples of substitution of halogenide ligands by formates on ruthenium complexes, see: (a) Mukaida, M.; Nomura, T.; Ishimori, T. *Bull. Chem. Soc. Jpn.* **1967**, *40*, 2462. (b) Mukaida, M.; Nomura, T.; Ishimori, T. *Bull. Chem. Soc. Jpn.* **1972**, *45*, 2143. (c) Clark, R. J. H.; Ferris, L. T. H. *Inorg. Chem.* **1981**, *20*, 2759. (d) Lehmann, H.; Wilkinson, G. *J. Chem. Soc., Dalton Trans.* **1981**, 191. (e) Lindsay, A.; Wilkinson, G.; Motevalli, M.; Hursthouse, M. B. *J. Chem. Soc., Dalton Trans.* **1985**, 2321.
(17) Hodson, E.; Simpson, S. J. *Polyhedron* **2004**, *23*, 2695.

Scheme 4. Room-Temperature Reaction of the Dimer $[RuX_2(p\text{-cym})]_2$ in the Presence of PPh_3 and Thallium Formate



X = I	benzene-d_6	22h	51	49
	MeOH-d_4	2h	0	100
X = Cl	MeOH-d_4	2h	0	100

appeared that methanol-d_4 was a suitable solvent. Indeed, in the presence of 1 equiv of PPh_3 and 2.4 equiv of thallium formate relative to ruthenium, the dimer $[RuI_2(p\text{-cym})]_2$ was quantitatively converted in less than 2 h to a single ruthenium complex (Scheme 4) with a ^{31}P NMR signal at 42.4 ppm and two ^1H NMR signals corresponding to formate ligands (δ = 7.68 and 7.67 ppm). These signals could be attributed to a species identical to the previously observed $[Ru(OCOH)_2PPh_3(p\text{-cym})]$ complex **B**. Under identical conditions, the dimer $[RuCl_2(p\text{-cym})]_2$ was also converted into complex **B** in less than 2 h. Complex **B** was isolated as a yellow powder in 74% yield under these conditions. The crystal structure of the complex was determined by single-crystal X-ray diffraction of the monoclinic orange crystals obtained by recrystallization of the complex from a dichloromethane/pentane mixture (Figure 1). This analysis confirmed the proposed formula of complex **B**. Complex **B** has a piano-stool geometry, as is often seen in transition metal complexes containing am η^6-arene ligand.[19] The triphenylphosphane and the two formate ligands are positioned at the three feet of the stool. In this complex, the two formates are not equivalent, as shown by the difference between the two Ru−O distances (2.104 and 2.109 Å). This geometry explains the presence of two close singlets in the ^1H NMR spectra corresponding to the two protons of the formate ligands (7.68 and 7.67 ppm in methanol-d_4).

In order to determine whether complex **B** was a catalytic precursor, we assessed its activity in the hydroarylation of triethoxyvinylsilane (**3a**). In the presence of an additional 2 equiv of triphenylphosphane and under conditions otherwise identical to those described previously, **B** turned out to be highly active in the alkylation of 1-acetonaphthone (**1a**), since it led to quantitative formation of **4aa** in less than 15 min (Scheme 5). In the same way, in the hydroarylation of triethoxyvinylsilane (**3a**) by *N-tert*-butyl-1-naphthaldimine (**2a**), the use of 5 mol

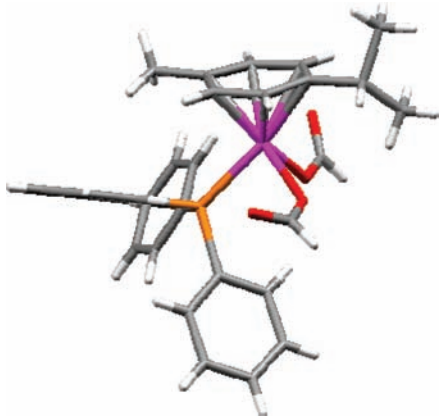
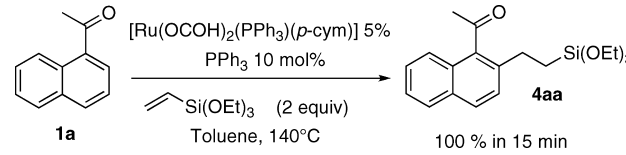


Figure 1. Crystal structure of complex **B**.

Scheme 5. Evaluation of the Catalytic Activity of Complex **B**



% of diformatoruthenium complex **B**, without the addition of triphenylphosphane, yielded complete formation of **5aa** in 3 h. Indeed, it is likely that this complex is a precursor of the active ruthenium species. We therefore examined the evolution of this complex under different conditions.

Evolution of Complex B. When complex **B** was dissolved in benzene-d_6 in the presence of 3 equiv of PPh_3, no reaction occurred at 26 °C (Figure 2a).

As the reaction mixture was gradually heated to 50 °C, ^1H NMR analysis showed the appearance of a second heptuplet (δ = 2.73 ppm, J = 7.0 Hz) with a doublet (δ = 1.08 ppm, J = 7.0 Hz); these signals were attributed to free *p*-cymene in solution and indeed to the decomplexation of *p*-cymene. At 45 °C, a new ruthenium complex **C** containing a *p*-cymene ligand began to appear. This complex was characterized by several ^1H NMR signals (Figure 2b): two doublets attributed to an arene complexed to metal (δ = 4.87 and 4.70 ppm, J = 6.2 Hz) and a heptuplet (δ = 2.40, J = 6.3 Hz) and a doublet (δ = 1.07, J = 6.3 Hz) attributed to the isopropyl group. The new species appeared to also include a hydride ligand (broad signal at δ = −7.1 ppm). It should be noted that at this temperature, the interpretation of ^{31}P NMR spectra is difficult because of the low resolution of the various signals. The observed ^1H NMR signals were tentatively assigned to the complex **C**, [RuH(OCOH)(PPh_3)(*p*-cym)] (Scheme 6). The reaction mixture was then left at a temperature of 50 °C, and its evolution was followed over time. After 10 min, the starting complex **B** completely disappeared, and a second, poorly resolved signal could be observed in the hydride region at a chemical shift of −18.3 ppm, corresponding to a second ruthenium species **D**

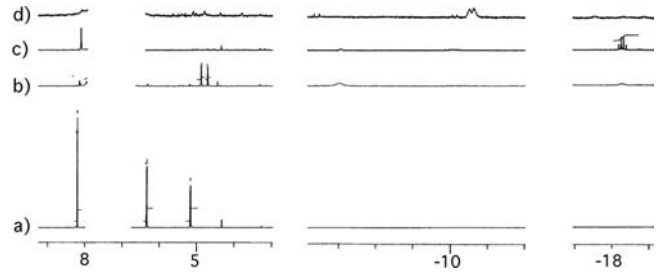
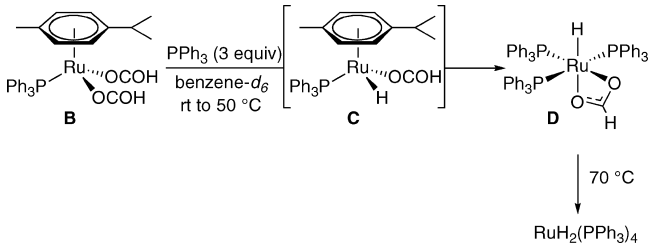


Figure 2. ^1H NMR spectra of the evolution of complex **B** with temperature: (a) room temperature; (b) 50 °C for 10 min; (c) 50 °C for 1 h; (d) 70 °C.

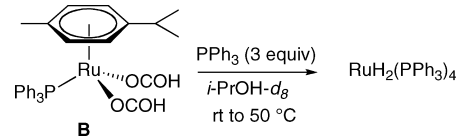
Scheme 6. Evolution of Complex **B** in C_6D_6



bearing no more *p*-cymene ligand. This species was the only observable one after 1 h at 50 °C (Figure 2c). The room temperature ^{1}H NMR analysis (Figure 2a) showed the presence of free *p*-cymene in solution and the quantitative formation of a ruthenium complex with one formate ligand (multiplet at $\delta = 8.06-8.08$) and a hydride ligand (quartet at -18.2 ppm, $J_{H-P} = 26.6$ Hz). The ^{31}P NMR spectrum indicated the presence of free triphenylphosphane ($\delta = -5.2$ ppm) and two new signals: a triplet ($\delta = 78.4$ ppm, $J_{P-P} = 27.7$ Hz) integrating to one triphenylphosphane and a doublet integrating to two triphenylphosphanes ($\delta = 43.6$ ppm, $J_{P-P} = 27.7$ Hz). The ruthenium species formed therefore seems to contain three triphenylphosphanes, two of which are magnetically equivalent, as well as formate and hydride ligands coupling with three equivalent phosphanes. The reaction mixture was analyzed by ^{13}C NMR spectroscopy, which showed the presence of different aromatic carbons and another signal at 172.8 ppm comparable to that observed for other formato ruthenium complexes described in the literature[20] and corresponding to a formate ligand complexed to the ruthenium in η^2 rather than η^1 fashion. Indeed, the intermediate **D** formed at 50 °C should be the complex [Ru(H)(η^2-OCOH)(PPh_3)$_3$] (Scheme 6). The latter is described in the literature as the product of the reaction between $RuH_2(PPh_3)_4$ and carbon dioxide, but it has never been analyzed by NMR.[21]

From this intermediate **D**, two mechanisms can be considered to explain the formation of Ru(0), which is postulated as the active species in the Murai reaction.[8b,22] In the first case, complex **D** could, by reductive elimination, lead to Ru(0) and 1 equiv of formic acid. A second possibility involves a second decarboxylation of the formate ligand to form a ruthenium dihydride, which would then react with the olefin present under the reaction conditions, leading to the Ru(0) species, as described by Murai and co-workers.[8b] ^{1}H NMR monitoring was repeated by heating complex **B** in benzene-d_6 at 50 °C for 1 h. Once the complex **D** had formed, the temperature was gradually increased

Scheme 7. Evolution of Complex **B** in 2-Propanol-d_8



to 70 °C. At that temperature, complex **D** disappeared, and a poorly resolved signal was observed at -10.2 ppm (Figure 2d). The latter was tentatively assigned to the complex $RuH_2(PPh_3)_4$ (Scheme 6).[23] The formation of $RuH_2(PPh_3)_4$ has also been described in the reaction between the complex [Ru(H)(η^2-OCOH)(PPh_3)$_3$] and triphenylphosphane.[21] However, it seems that the complex $RuH_2(PPh_3)_4$ is not stable under the reaction conditions at 70 °C, since the amount of hydride signal decreases very quickly. Upon the return to room temperature after 30 min at 70 °C, the hydride signals had totally disappeared, and according to the ^{31}P NMR analysis, only free triphenylphosphane was present in the mixture. It is likely that the ruthenium dihydride evolved into a metal ruthenium species, as evidenced by the presence of a black precipitate in the NMR tube.

On the other hand, when a solution of complex **B** and 3 equiv of PPh_3 was heated in 2-propanol-d_8 at 50 °C for 1 h, a precipitate quickly formed. ^{1}H NMR analysis of this precipitate in benzene-d_6 showed the presence of a multiplet between -9.91 and -10.34 ppm, integrating to two protons. This signal, at 25 °C, consists of a doublet of triplets superimposed on a larger background noise signal ($\delta = -10.16$ ppm, $J_{H-P} = 35.0$ and 40.8 Hz). This type of signal has been described in the literature for $RuH_2(PR_3)_4$-type complexes with the two hydrides in cis positions (Scheme 7).[24] In the ^{31}P NMR spectrum, two multiplets, each integrating to two triphenylphosphanes, were observed ($\delta = 49.1-49.5$ and $41.0-41.4$ ppm), confirming the formation of $RuH_2(PPh_3)_4$.[23] It should be noted that this complex appeared to be relatively stable in 2-propanol at room temperature, which was not the case in benzene (see above). Indeed, formation of the $RuH_2(PPh_3)_4$ complex was much faster in 2-propanol than in benzene, and the intermediate complex **D** was not observed; the mechanism appears to be different and seems to imply the rapid decarboxylation of the two formates. It is also possible to envisage a mechanism similar to that observed in benzene (see above), with the intermediate formation of **D**, which would evolve much more quickly in 2-propanol. Overall, these studies on the evolution of the catalytic system formed in situ confirmed the formation of a dihydride ruthenium complex via the formation of a diformatoruthenium complex.

Indeed, under catalytic conditions, in the presence of only 3 equiv of triphenylphosphane, one could also propose the formation of an unsaturated ruthenium species, [$RuH_2(PPh_3)_3$], eventually complexed with vinylsilane or the activated substrate. The structure of the in situ-generated complex is thus very similar to Murai's catalyst $RuH_2(CO)(PPh_3)$, and as suggested

(18) For some examples of arene exchange on ruthenium complexes, see: (a) Bennett, M. A.; Neumann, H.; Thomas, M.; Wang, X. Q.; Pertici, P.; Salvadori, P.; Vitulli, G. *Organometallics* **1991**, *10*, 3237. (b) Luo, S.; Rauchfuss, T. B.; Rheingold, A. L. *J. Organomet. Chem.* **1994**, *472*, 295.

(19) Marr, A. C.; Nieuwenhuyzen, M.; Pollock, C. L.; Saunders, G. C. *Organometallics* **2007**, *26*, 2659.

(20) (a) Suzuki, H.; Kakigano, T.; Igarashi, M.; Tanaka, M.; Moro-Oka, Y. *J. Chem. Soc., Chem. Commun.* **1991**, 283. (b) Jia, G.; Meek, D. W. *Inorg. Chem.* **1991**, *30*, 1953. (c) Whittlesey, M. K.; Perutz, R. N.; Moore, M. H. *Organometallics* **1996**, *15*, 5166. (d) Gao, Y.; Jennings, M. C.; Puddephatt, R. J. *Organometallics* **2001**, *20*, 1882. (e) Gandhi, T.; Nethaji, M.; Jagirdar, B. R. *Inorg. Chem.* **2003**, *42*, 667. (f) Burling, S.; Kociok-Köhn, G.; Mahon, M. F.; Whittlesey, M. K.; Williams, J. M. J. *Organometallics* **2005**, *24*, 5868.

(21) (a) Komiya, S.; Yamamoto, A. *J. Organomet. Chem.* **1972**, *46*, C58. (b) Kolomnikov, I. S.; Gusev, A. I.; Aleksandrov, G. G.; Lobeeva, T. S.; Struchkov, Y. T.; Vol'pin, M. E. *J. Organomet. Chem.* **1973**, *59*, 349. (c) Komiya, S.; Yamamoto, A. *Bull. Chem. Soc. Jpn.* **1976**, *49*, 784.

(22) For mechanistic investigations of the Murai reaction, see ref 8a and: (a) Matsubara, T.; Koga, N.; Musaev, D. G.; Morokuma, K. *J. Am. Chem. Soc.* **1998**, *120*, 12692. (b) Guari, Y.; Sabo-Etienne, S.; Chaudret, B. *J. Am. Chem. Soc.* **1998**, *120*, 4228. (c) Matsubara, T.; Koga, N.; Musaev, D. G.; Morokuma, K. *Organometallics* **2000**, *19*, 2318. (d) Kakiuchi, F.; Ohtaki, H.; Sonoda, M.; Chatani, N.; Murai, S. *Chem. Lett.* **2001**, *30*, 918. (e) Berger, D.; Göbel, A.; Imhof, W. *J. Mol. Catal. A* **2001**, *165*, 37. (f) Jazzar, R. F. R.; Mahon, M. F.; Whittlesey, M. K. *Organometallics* **2001**, *20*, 3745.

(23) Gómez-Bengoa, E.; Cuerva, J. M.; Mateo, C.; Echavarren, A. M. *J. Am. Chem. Soc.* **1996**, *118*, 8553.

(24) Meakin, P.; Muetterties, E. L.; Jesson, J. P. *J. Am. Chem. Soc.* **1973**, *95*, 75.

by Trost et al.,[25] the presence of the CO ligand is not necessary for this C−H activation toward C−C bond formation. As described earlier,[22] the next step would involve the reduction of the ruthenium dihydride to ruthenium(0) upon reaction with the alkene present in the reaction mixture, and the overall reaction mechanism must be very similar to those previously proposed.[22]

Conclusion

We have demonstrated for the first time the possibility of generating in situ from a stable and readily available ruthenium(II) source a highly active ruthenium catalyst for C−H bond activation. The versatility of this catalytic system has been demonstrated, as it offers the possibility of modifying the electronic and steric properties of the catalyst by fine-tuning of the ligands, allowing functionalization of various substrates. Aromatic ketones and imines could be easily functionalized by the reaction with either vinylsilanes or styrenes, depending on the electronic and steric nature of the ligand.

Moreover, variable-temperature NMR experiments and the isolation of an intermediate ruthenium complex, [$Ru(OCOH)_2$-PPh_3(*p*-cym)], have provided some insights into the generation of the active catalytic ruthenium species in this reaction.

Experimental Section

Typical Procedure. A septum-capped vial equipped with a magnetic stirring bar was charged with [$RuCl_2$(*p*-cym)]$_2$ complex (15.3 mg, 0.025 mmol), sodium formate (20.4 mg, 0.3 mmol), and monophosphane ligand (see the tables for amounts). The vial was closed, evacuated under vacuum for 10 min, and placed under an argon atmosphere. Degassed toluene (1 mL) was added, and the mixture was degassed using two vacuum/argon cycles. To this solution were added the substrate (1 mmol) and the vinylsilane (2 equiv) or the styrene (3−4 equiv), after which the mixture was stirred for 10 min at room temperature and then placed into a preheated bath at 140 °C for 20 h (completion of the reaction was checked by GC). After the reaction vessel was cooled to room temperature, the reaction mixture was purified by column chromatography.

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Supporting Information Available: Experimental procedures, compound descriptions, and crystallographic data for complex **B** (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

JA9017489

(25) Trost, B. M.; Imi, K.; Davies, I. W. *J. Am. Chem. Soc.* **1995**, *117*, 5371.