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Lionel V. Graux, Michel Giorgi, Gérard Buono, Hervé Clavier. [RuCl2(η6-p-cymene)] complexes bearing phosphinous acid ligands: preparation, application in C–H bond functionalization and mechanistic investigations. Dalton Transactions, 2016, 10.1039/c5dt04683a . hal-01409748

HAL Id: hal-01409748

https://hal.science/hal-01409748v1

Submitted on 6 Dec 2016

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Journal Name

ARTICLE

Received 00th January 20xx,

Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

www.rsc.org/

[$RuCl_2(\eta^6$-*p*-cymene)]complexes bearing phosphinous acid ligands: preparation, application in C-H bond functionalization and mechanistic investigations

LionelV. Graux,[a]MichelGiorgi,[b]Gérard Buono[a]and HervéClavier[a*]

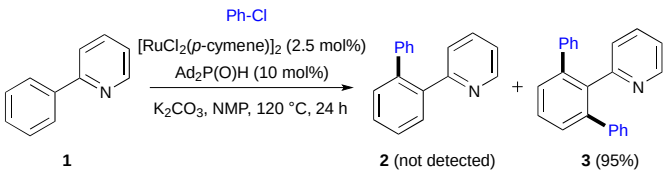
A series of [$RuCl_2(\eta^6$-*p*-cymene)]complexes bearing phosphinous acid (PA) ligands has been straightforwardly prepared from the dimer [$RuCl_2$(*p*-cymene)]$_2$ and secondary phosphine oxides (SPOs), and fully characterized. The steric parameter quantification of PAs, other L ligands and η^6-*p*-cymene allowed a better comprehension of the coordinationchemistryof this type of complexes and explained the absence of coordination in the case of bulky SPOs such as $Ad_2P(O)H$. These complexes were tested in theC-H activation/functionalization of 2-phenylpyridine and a good activity was obtained at 80 °C for the complex exhibiting the highest steric bulk. A study on halide effects,either on the ruthenium complex or for the aryl halide partner,has also been carried out and showed drastic differences. Further investigations on halides effects were performed notably using cationic ruthenacycle which was found to be an intermedaite of the reaction. In order to rationalize the role played by the phosphinous acid, a mechanism involving a concerted metallation deprotonation favored by a phosphinito species has been proposed.

Introduction

Considered for a long time as a main challenge in organic synthesis, the C-H activation/functionalization has emerged recentlyas a powerful tool to prepare complex molecules starting from readily available raw materials.[1]In this quest, the use of transition metal catalysis is at the origin of groundbreaking discoveries and now various catalytic systems using palladium,[2] rhodium,[3] ruthenium,[4]copper,[5]platinum,[6]nickel,[7]cobalt,[8] f-block elements,[9] etc are recognized to be highly efficient for C-H bond activation. In these systems, major advances were accomplished by clear mechanistic studies which allowed deeper understanding of the mechanism, notably the role of ligands and/or additives. For instance, Catellani developed a Pd-catalyzed regioselective C-H bond functionalization of arenes using norbornene as a covalent linker.[10] Alternatively, it was demonstrated that C-H activation could occur according to a σ-bond metathesis pathway,[11] so called concerted metallation deprotonation (CMD). In such process, the intermolecular abstraction of the proton by acetato ligands favors the metallacycle formation.[12]

Whereas pioneering works on catalytic C(sp^2)-H activation were achieved using Ru-based complexes,[13] catalytic systems using Pd or Rh have attracted much attention during the last decade. Nevertheless, interesting Ru-based catalytic systems have been reported in the literature mainly using the dimer [$RuCl_2$(*p*-cymene)]$_2$ in association with carboxylate additives.[4,14] Our research involving secondary phosphine oxides (SPO) and phosphinous acids (PA) as ligands in transition metal catalysis,[15] the catalytic system using [$RuCl_2$(*p*-cymene)]$_2$ and SPO developed by Ackermann in 2005 caught our attention (Scheme 1).[16]A Ru(II) complex, prepared *in situ* from [$RuCl_2(\eta^6$-*p*-cymene)]$_2$ and sterically hindered diadamantylphosphine oxide, was found very efficient for *ortho* C-H bond activation of the 2-phenylpyridine **1** and coupling with chlorobenzene to yield quantitatively compound **3**without any traces of monoarylated**2**. Moreover, this catalytic system showed a high efficiency for various substrates.[17] We wonderedabout the role played by the SPO or its tautomeric phosphinous acidform in the C-H activation process. Whereas several mechanistic hypothesis have been postulated,[4,17c]none of them was further investigated.

Therefore, we wished to investigate the mechanism of this C-H bond activation/functionalization through the synthesis of well-defined [$RuCl_2(\eta^6$-*p*-cymene)(PA)] complexes and the



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Electronic supplementary information (ESI) available: Experimental and spectral data. CCDC 1434226-1434232. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/x0xx00000x

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Scheme 1C-H activation/functionalization mediated by $RuCl_2$(*p*-cymene)]$_2$and SPO.

study of their performances in catalysis. Control experiments have been carried out to corroborate mechanistic proposal. The results of our study are reported therein.

Results and discussion

We started tostudythe coordination chemistry of SPOs with [$RuCl_2$(*p*-cymene)]$_2$. Thesynthesis of [$RuCl_2$(η^6-arene)(PA)]has been previously reported in the literature,[18] notably two complexes[Ru(η^6-*p*-cymene)Cl_2(PA)]**5a** and **5l**were already described by the groups ofTyler[19] and Leung[20]respectively (Fig. 1) and **5a**has been successfully applied to nitrile hydratation.[19,21]

Following the same procedure, [$RuCl_2$(*p*-cymene)]$_2$ was treated with various secondary phosphine oxides **4**in THF at 25 °C to afford the expected complexes **5** (Table 1).[22] Of note, in dichloromethane ortoluene, the reaction was sluggish compared to THF. Expected for $Cy_2P(O)H$ **4b** which required 24 h of reaction, other SPOs, either symmetrical ones (entries 2-4) or unsymmetrical ones (entries 7-11), were found very reactive.After only 2-3 h, complexes **5** were isolated in almost quantitative yields. Surprisingly, with bulky SPOs such as $Ad_2P(O)H$ **4f** or $tBu_2P(O)H$ **4g**, we were unable to obtain the corresponding complexes **5** (entries 5 and 6). Despite prolonged reaction times and/or heating to 110 °C, their formation could not be detected by NMR spectroscopy.

The well-defined [$RuCl_2$(η^6-*p*-cymene)(PA)] **5** were characterized by ^{1}H,^{23}13C, and ^{31}P NMR spectroscopy, as well

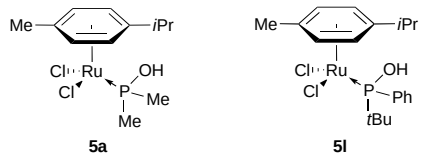
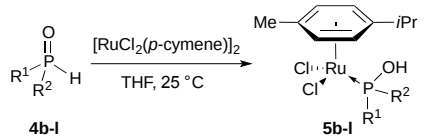


Fig. 1 [$RuCl_2$(η^6-*p*-cymene)(PA)] complexes described in the literature.

Table 1 Preparation of well-defined [$RuCl_2$(η^6-*p*-cymene)(PA)] complexes.[a]



Entry	R^1	R^2	t (h)	Complex	Yield (%)
1	Cy	Cy	24	**5b**	89
2	Ph	Ph	2	**5c**	96
3	*p*-F-C_6H_4	*p*-F-C_6H_4	6	**5d**	84
4	3,5-Me_2-C_6H_3	3,5-Me_2-C_6H_3	3	**5e**	91
5[b]	Ad	Ad	24	**5f**	NR
6[b]	*t*Bu	*t*Bu	24	**5g**	NR
7	Me	Ph	3	**5h**	74
8	*n*Bu	Ph	3	**5i**	53
9	Bn	Ph	3	**5j**	88
10	Cy	Ph	3	**5k**	98
11	*t*Bu	Ph	3	**5l**	99

[a] Reaction conditions: [$RuCl_2$(η^6-*p*-cymene)]$_2$, SPO (2.2 equiv.), THF (0.5M), 25 °C. [b]reaction performed in 1,4-dioxane at 110 °C. NR = No reaction.

Table 2 $^{31}P\{^1H\}$ NMR spectral data for SPOs **4** and Ru-complexes **5**.[a]

Entry	SPO	$^{31}P\{^1H\}$ (ppm)	Complex **5**	$^{31}P\{^1H\}$ (ppm)
1	**4b**	50.0	**5b**	129.3
2	**4c**	21.4	**5c**	107.1
3	**4d**	18.2	**5d**	105.6
4	**4e**	22.8	**5e**	107.0
5	**4h**	20.2	**5h**	109.5
6	**4i**	28.0	**5i**	113.1
7	**4j**	29.6	**5j**	109.4
8	**4k**	36.7	**5k**	114.2
9	**4l**	47.4	**5l**	115.5

[a] Measured in $CDCl_3$ at 25 °C.

as mass spectrometry. The coordination of the phosphinous acid to the metallic center through the phosphorus atom was confirmed by NMR spectroscopies and the absence of ^1J(P,H) coupling. Moreover, ^{31}P NMR spectroscopies showed new resonances between 105-130 ppm with a significant shift to lower field compared to SPOs ($\Delta\delta$ between 68 and 89 ppm, Table 2).

To establish unambiguously the structure of [$RuCl_2$(η^6-*p*-cymene)(PA)] complexes **5**, suitable crystals for single-crystal X-ray diffraction studies were obtained for most of the compounds. As depicted in Fig. 2, all complexes adopt a distorted octahedral structure with the expected three-legged pseudotetrahedral "piano-stool" geometry around the Ru atom and the η^6-coordination of the *p*-cymene. Two chlorine atoms and the phosphorus occupy the other three positions. Bond lengths are similar to those reported for analogous complexes (Table 3); the Ru-Cl bond distancesrangefrom 2.3943(10)to 2.4395(7)Å, the Ru-P bond lengthsfrom2.3009(8)to 2.3680(7)Å and the longest distances have been observed with cyclohexyl and *tert*-butyl P-substituents (entries 1, 6 and 7). This seems to be the result of a higher steric congestion of PA ligands. The P-O bond lengths (all close to 1.60 Å) are consistent with a P-O single bond.The O···Cl distances ranging from 2.961(2)to3.070(2) Å – except for **5h**, 3.175(2) Å, entry 4 – indicate an hydrogen bonding with chlorines.Of note, with **5h**, the hydrogen bonding takes place intermolecularly.

In order to gain more insights onto the coordination chemistry of [$RuCl_2$(*p*-cymene)(L)] and particularly to address the issue of absence of reaction with bulky SPOs $Ad_2P(O)H$ **4f** or $tBu_2P(O)H$

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4g, we quantified the steric parameter of phosphinous acids and other ligands L (phosphine, phosphite and *N*-heterocyclic carbene (NHC)) through the percent buried volume (%V_{bur}).[24,25] Selected values have been gathered in table 4.[23] The %V_{bur} for PA ligands span from 21.9 to 24.6%. These values are significantly lower than those calculated on AuCl(PA) complexes.[15g] As expected Ph_2POH is more sterically demanding than Ph_2PH (entries 3 and 9) but less than Ph_2PCH_2OH, Ph_2PnBu, PPh_3 or $P(OPh)_3$ (entries 9-13). The highest %V_{bur} calculated in [$RuCl_2$(*p*-cymene)(L)] complexes is for the NHC IMes (1,3-dimesityl-imidazol-2-ylidene) (27.9%) which is in the lower range for this ligand (entry 14).[24] These low %V_{bur} values and their narrow range attest probably that the other ligands

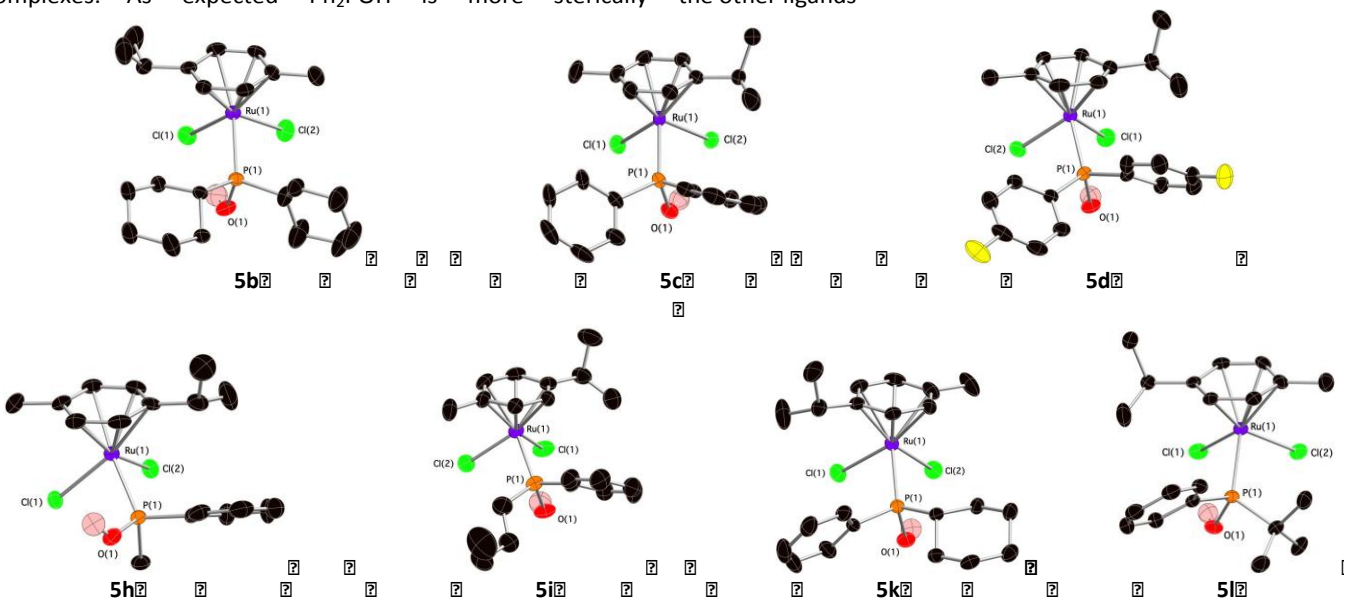

Fig. 2 Molecular structures of complexes **5b-d**, **5h-i** and **5k-l** represented at 50% ellipsoid probability. Most of the H atoms have been omitted for clarity.

Table 3 Selected bond lengths (Å) for complexes [$RuCl_2$(*p*-cymene)(PA)] **5b-d**, **5h-i** and **5k-l**.

Entry	Complex	Ru(1)-Cl(1) (Å)	Ru(1)-Cl(2) (Å)	Ru(1)-P(1) (Å)	P(1)-O(1) (Å)	O···Cl (Å)	Ru(1)-C_{avg} (Å)
		2.4323(10)	2.3943(10)	2.3376(9)	1.600(3)	2.988(3)	2.203(4)
1	**5b**	2.4320(10)	2.4198(9)	2.3379(9)	1.602(3)	3.005(3)	2.214(4)
		2.4296(10)	2.4072(9)	2.3445(10)	1.612(3)	3.027(3)	2.215(4)
2	**5c**	2.4171(8)	2.4156(8)	2.3120(8)	1.602(2)	3.070(2)	2.216(3)
3	**5d**	2.4147(9)	2.3970(8)	2.3009(8)	1.605(2)	3.011(3)	2.212(3)
4	**5h**	2.4024(6)	2.4197(6)	2.3130(6)	1.6034(19)	3.175(2)	2.210(3)
5	**5i**	2.4295(11)	2.4032(11)	2.3017(10)	1.604(3)	2.988(3)	2.209(4)
6	**5k**	2.3966(8)	2.4389(9)	2.3342(8)	1.601(2)	3.009(2)	2.212(3)
7	**5l**	2.4395(7)	2.4124(7)	2.3680(7)	1.6098(19)	2.961(2)	2.214(3)

in the coordination sphere of the Ru are sterically demanding and the L ligand has therefore to minimize its size. The %V_{bur} of the η^6-*p*-cymene has been also quantified in 24 X-ray structures and the size of this ligand was found relatively invariant with an average value of 47.5% and a standard deviation of 0.35%.[23] As intuitively expected, the η^6-*p*-cymene occupies almost half of the Ru coordination sphere and does not show any structural flexibilities. Therefore, the coordination of sterically hindered ligands, such as Ad_2POH or tBu_2POH, seems unlikely.Indeed, calculations performed on other complexes shown that %V_{bur} of tBu_2POH and Ad_2POH are around 30.5 and 31.5, respectively.[23]

Having prepared a series of well-defined [$RuCl_2$(η^6-cymene)(PA)], we have then tested their catalytic performances in C-H activation using 2-phenylpyridine **1** as benchmark substrate using Ackermann's conditions (Table 5). A control experiment showed that at 120 °C, [$RuCl_2$(*p*-cymene)]$_2$ without addition of SPO was competent for C-H functionalization since 88% of diarylated product **3** was isolated (entry 1). At 100°C, only minute amounts of products **2** and **3** were obtained with [$RuCl_2$(*p*-cymene)]$_2$ (entry 2) whereas adding either 5 other 10 mol% of Ad_2POH allowed to isolated around 80% of diarylated product **3** (entries 3 and 4). However, lowering the reaction temperature to 80 °C led to the loss of activity of the dimer [$RuCl_2$(*p*-cymene)]$_2$ (entry 5). In one hand, at this temperature, [$RuCl_2$(*p*-cymene)]$_2$ in association with $Ad_2P(O)H$ **4f** gave only small amounts of **2** and **3** (entry 6). On the other hand, well-defined [$RuCl_2$(η^6-cymene)(PA)] **5a-e** and **5i-k** were found much more competent and significant quantities of C-H functionalized products were isolated (entries 7-14). Since reactions did not reach completion, ca. 1:1 mixtures of mono- and diarylated products

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Table 4 Percent of buried volume of various ligands L in [$RuCl_2(\eta^6$-*p*-cymene)(L)] complexes.[a]

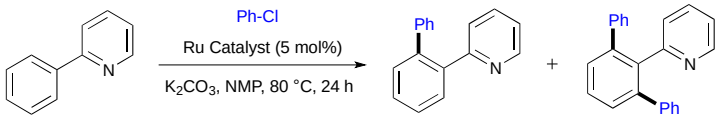
Entry	L	d(Ru-L) (Å)	%V_{bur}(L)
1	Me_2POH	2.3078(10)	21.9
2	Cy_2POH	2.3376(9)	24.4
3	Ph_2POH	2.3120(8)	24.6
4	$(p\text{-}F\text{-}C_6H_4)_2POH$	2.3009(8	24.6
5	MePhPOH	2.3130(6)	22.7
6	*n*BuPhPOH	2.3017(10)	22.7
7	CyPhPOH	2.3342(8)	24.1
8	*t*BuPhPOH	2.3680(7)	24.4
9	Ph_2PH	2.313(2)	23.2
10	Ph_2PCH_2OH	2.3516(8)	25.1
11	Ph_2PnBu	2.352(2)	25.6
12	PPh_3	2.3438(6)	26.8
13	$P(OPh)_3$	2.2642(8)	24.7
14	IMes	2.142(4)	27.9

[a] Parameters used for Samb*V*ca calculations: 3.50 Åfor the sphere radius, exact distances between the ligand and the metal were considered,hydrogen atoms were omitted and bond radii scaled by 1.17.

were obtained. Well-defined complexes performed slightly better than *in situ*-generated complexes (entries 14 and 15) and addition of an extra quantity of SPO reduced the catalyst activity.[23] To our delight, with $RuCl_2(\eta^6$-*p*-cymene)(*t*BuPhPOH)] **5l**, only compound **3** was formed with an almost quantitative yield (entry 16). Of note, after only 2 h of reaction, a 1:1 mixture of mono- and diarylated products was observed with **5l** (entry 17). The electronic properties of phosphinous acids did not influence the catalytic activities of the resulting complexes. For example Ph_2POH-containing **5c** performed better than **5b** bearing themore electron rich Cy_2POH and than **5d** bearing electron withdrawing ligand $(p\text{-}F\text{-}C_6H_4)_2POH$ (entries 8-10). In contrast, higher activities have been obtained for more sterically demanding PA ligands, ie. *t*BuPhPOH and $(3,5\text{-}Me_2\text{-}C_6H_3)_2POH$ (entries 16 and 11, respectively). Importantly, complexes bearing phosphine or phosphite exhibited interesting activities in C-H activation (entries 18-20). In particular, $[RuCl_2(\eta^6$-*p*-cymene)$(PPh_3)]$ was found more selective for mono-functionalization of 2-phenylpyridine **1** (entry 18).

In Ru-mediated C-H activation, the anionic ligands played an important role, for example carboxylate-containing complexes are extremely efficient due to chelation-assisted C–H activations.[1k,4a]Surprisingly, to the best of our knowledge, complexes bearing bromide and iodide ligands have not been investigated so far. Bromide and iodide counterparts bearing *t*BuPhPOH phosphinous acid were prepared with good yield following the same protocol than for chloride analogues (**6l** and **7l** respectively, Scheme 2). The activity of these catalysts was compared in C-H functionalization of 2-phenylpyridine **1** and as a function of the aryl halide partner (Table 6). Unexpectedly, drastic differences were observed as only low yields of C-H functionalization and with an almost equimolar

Table 5 Evaluation of catalysts performances in C-H bond activation .[a]



1 **2** **3**

Entry	Catalyst	Additive	Yield (%) **2**	Yield (%) **3**
1[b]	$[RuCl_2(p\text{-cymene})]_2$		0	88
2[c]	$RuCl_2(p\text{-cymene})]_2$		8	2
3[c]	$RuCl_2(p\text{-cymene})]_2$	$Ad_2P(O)H$ **4f** (5 mol%)	0	80
4[c]	$RuCl_2(p\text{-cymene})]_2$	$Ad_2P(O)H$ **4f** (10 mol%)	0	83
5	$[RuCl_2(p\text{-cymene})]_2$		0	0
6	$[RuCl_2(p\text{-cymene})]_2$	$Ad_2P(O)H$ **4f**(10 mol%)	7	3
7	$[RuCl_2(\eta^6\text{-}p\text{-cymene})(Me_2POH)]$ **5a**		14	15
8	$[RuCl_2(\eta^6\text{-}p\text{-cymene})(Cy_2POH)]$ **5b**		12	11
9	$[RuCl_2(\eta^6\text{-}p\text{-cymene})(Ph_2POH)]$ **5c**		27	22
10	$[RuCl_2(\eta^6\text{-}p\text{-cymene})((p\text{-}F\text{-}C_6H_4)_2POH)]$ **5d**		19	11
11	$[RuCl_2(\eta^6\text{-}p\text{-cymene})((3,5\text{-}Me_2\text{-}C_6H_3)_2POH)]$ **5e**		32	32
12	$[RuCl_2(\eta^6\text{-}p\text{-cymene})(n\text{BuPhPOH})]$ **5i**		19	19
13	$[RuCl_2(\eta^6\text{-}p\text{-cymene})(\text{BnPhPOH})]$ **5j**		19	11
14	$[RuCl_2(\eta^6\text{-}p\text{-cymene})(\text{CyPhPOH})]$ **5k**		22	54
15	$[RuCl_2(p\text{-cymene})]_2$	CyPhP(O)H **4k** (5 mol%)	21	19
16	$[RuCl_2(\eta^6\text{-}p\text{-cymene})(t\text{BuPhPOH})]$ **5l**		0	89
17[d]	$[RuCl_2(\eta^6\text{-}p\text{-cymene})(t\text{BuPhPOH})]$ **5l**		14	13
18	$[RuCl_2(\eta^6\text{-}p\text{-cymene})(PPh_3)]$		58	6
19	$[RuCl_2(\eta^6\text{-}p\text{-cymene})(PCy_3)]$		18	5
20	$[RuCl_2(\eta^6\text{-}p\text{-cymene})(P(OPh)_3)]$		19	15

[a] Reaction conditions: 2-phenylpyridine**1** (142 µL, 1 mmol), chlorobenzene (220µL, 2.2 mmol, 2.2 equiv.), K_2CO_3 (415 mg, 3 mmol, 3 equiv.), 5 mol% of Ru complex (2.5 mol% for $[RuCl_2(p\text{-cymene})]_2$), NMP (2 mL), 80 °C, 24 h. [b] Reaction performed at 120 °C. [b] Reaction performed at 100 °C. [d] Reaction time: 2h.

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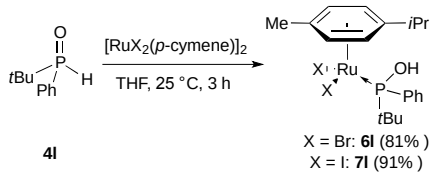
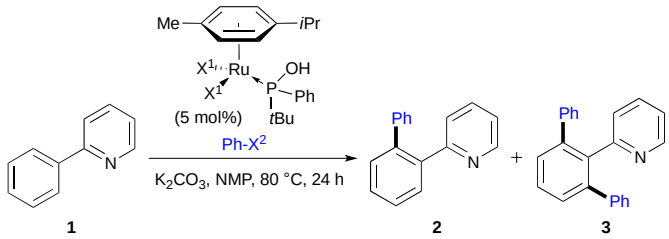
mixture of mono- and diarylation were obtained (entries 2 and 3). Moreover, whereas aryl bromides are regularly used as coupling partner,[26] at 80 °C, they exhibited a significantly lower activity than their chloride counterpart (entries 4-6).[27] We assume that this is due to an exchange of halogens between the aryl halide to the metal center occurring through the oxidative addition. Halide effects in transition metal catalysis are often difficult to rationalize,[28] however, we believe that the iodide atoms increase the congestion around the metal center and decreases its reactivity.[29]

From these results, a halide inhibition was suspected; the chlorine dependence was therefore investigated through the use of additives (Table 7). The addition of one equivalent of LiCl in the reaction mixture quenched indeed the C-H activation process (entries 1 and 2). A significant loss of activity was also observed with 1 equiv. of tetrabutylammonium chloride (entry 3). Nevertheless, addition of a stoichiometric amount of silver salt did not boost the catalytic performances of complexes exhibiting a moderate activity such as complexes



Scheme 2 Synthesis of bromide- and iodide-containing [RuX$_2$(η^6-*p*-cymene)(PA)] complexes.

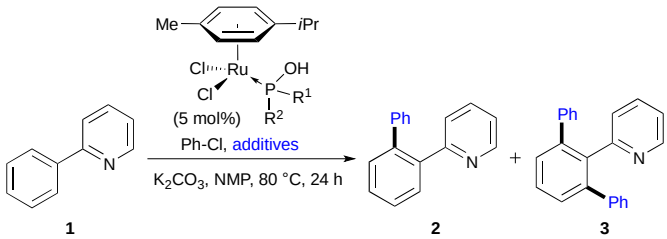
Table 6 Halogen effect in C-H activation.[a]



Entry	X^1 (complex)	Ph-X^2	Yield (%) 2	Yield (%) 3
1	Cl (**5l**)	Ph-Cl	0	89
2	Br (**6l**)	Ph-Br	23	18
3	I (**7l**)	Ph-I	14	8
4	Cl (**5l**)	Ph-Br	6	21
5	Cl (**5l**)	Ph-I	3	5
6	Br (**6l**)	Ph-I	3	7

[a] Reaction conditions: 2-phenylpyridine**1** (142 µL, 1 mmol), aryl halide (2.2 mmol, 2.2 equiv.), K_2CO_3 (415 mg, 3 mmol, 3 equiv.), complex (5 mol%), NMP (2 mL), 24 h.

Table 7 Chlorine dependence in C-H activation.[a]



Entry	Complex**5**	Additives	Yield (%) **2**	Yield (%) **3**
1	**5l**(R^1,R^2 = Ph,*t*Bu)	None	0	89
2	**5l**(R^1,R^2 = Ph,*t*Bu)	LiCl (1 equiv.)	0	0
3	**5l** (R^1,R^2 = Ph,*t*Bu)	nBu$_4$NCl (1 equiv.)	9	6
4	**5a**(R^1,R^2 = Me,Me)	None	14	15
5	**5a**(R^1,R^2 = Me,Me)	$AgBF_4$ (5 mol%)	14	16
6	**5a**(R^1,R^2 = Me,Me)	$AgBF_4$ (1 equiv.)	0	0
7	**5b**(R^1,R^2 = Cy,Cy)	None	12	11
8	**5b**(R^1,R^2 = Cy,Cy)	$AgBF_4$ (5 mol%)	9	8
9	**5b**(R^1,R^2 = Cy,Cy)	$AgBF_4$ (1 equiv.)	2	2

[a] Reaction conditions: 2-phenylpyridine**1** (142 µL, 1 mmol), chlorobenzene (220 µL, 2.2 mmol, 2.2 equiv.), K_2CO_3 (415 mg, 3 mmol, 3 equiv.), complex (5 mol%), NMP (2 mL), 24 h.

5a and **5b** (entries 5 and 8). Higher quantities of silver salt led to the inhibition of the C-H functionalization (entries 6 and 9). These results suggest that chlorine atoms play a key role in the C-H activation process.

In order to gain insight into the mechanism, in particular the role of the PA ligand, and as PAs are considered as labile ligands due to a weak M-PA bond,[15d] we attempted to determine if the PA remains in the coordination sphere of the ruthenium all along the catalytic cycle. For this purpose, the ruthenium cyclometallated complex **8** was prepared[30] and tested in catalysis (Table 8). As anticipated, at 120 °C, this catalyst performed well with 91% of diarylated compound **3** isolated (entry 1). However, at 80 °C, no reaction occurred, even when the ligand *t*BuPhP(O)H **4l** was added (entries 2 and 3). In one hand, the addition of a substoichiometric amount of silver salt such $AgBF_4$ and $AgSbF_6$ allowed the formation a small quantities of products **2** and **3** (entries 4 and 5). On the other hand, the combination of the silver salt with OPS *t*BuPhP(O)H **4l** led to restore almost completely the activity of the catalytic system (entries 6 and 7).

We were also able to prepare quantitatively the cationic ruthenacycle **9c** bearing a phosphinous acid ligand by the treatment of complex **8** with OPS **4c** in presence of silver tetrafluoroborate in stoichiometric amount. Unfortunately **9c** was found to exhibit no activity in our optimal conditions (80

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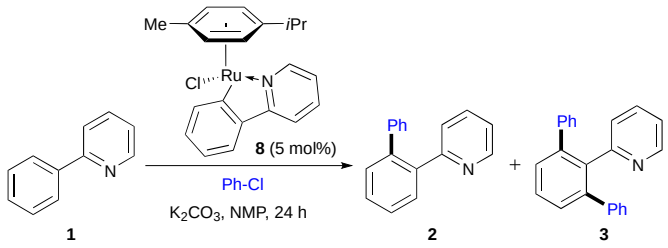
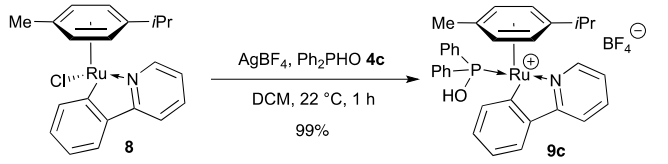
Table 8 Control experiements with ruthenacycle **8**.[a]



Entry	Additives	T (°C)	Yield (%) 2	3
1	None	120	0	91
2	None	80	0	0
3	*t*BuPhP(O)H **4l** (5 mol%)	80	0	0
4	$AgBF_4$ (6 mol%)	80	5	4
5	$AgSbF_6$ (6 mol%)	80	7	8
6	$AgBF_4$ (6 mol%), *t*BuPhP(O)H **4l** (5 mol%)	80	26	52
7	$AgSbF_6$ (6 mol%), *t*BuPhP(O)H **4l** (5 mol%)	80	26	56

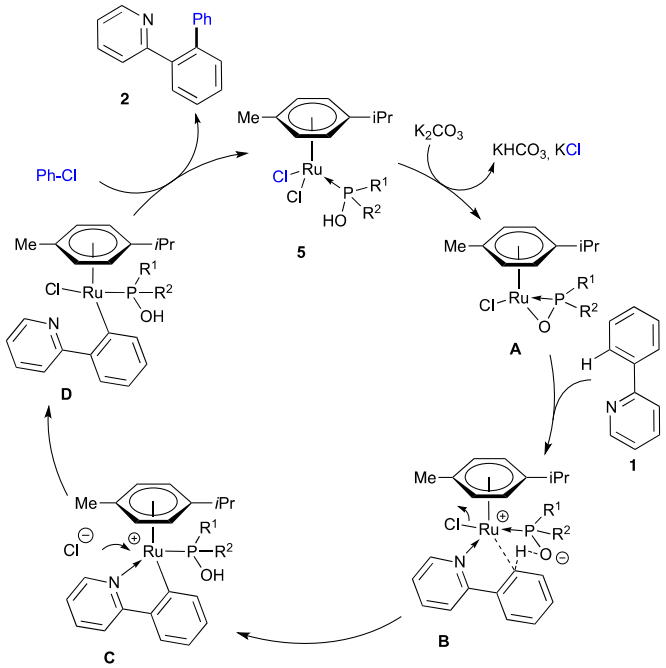
[a] Reaction conditions: 2-phenylpyridine**1** (142 µL, 1 mmol), chlorobenzene (220µL, 2.2 mmol, 2.2 equiv.), K_2CO_3 (415 mg, 3 mmol, 3 equiv.), complex **8** (21.3 mg, 5 mol%), NMP (2 mL), 24 h.



Scheme 3 Preparation of the cationic ruthenacycle **9c**.

°C). However, when this reaction was preformed in presence of 5 mol% of tetrabutylamonium chloride, **9c**displayed a moderate activity with the formation of 11% of mono arylated product **2** and 14% of **3**. This represents only a slight decrease of performance compared to catalyst **5c** (27% of **2** and 22% of **3**, Table 5, entry 9). To further investigate this chlorine effect, complex **9c** was treated with 5 equiv. of LiCl in $CDCl_3$ at room temperature, and rapidly the ^{31}P NMR spectroscopy showed a new resonance at 108.4 ppm with complete disappearance of the signal at 114.7 ppm after only one hour. Unfortunately, this new compound was found to be unstable and could not be isolated and fully characterized.

With these results in mind, we propose the following mechanism for C-H activation/functionalization catalyzed by $[RuCl_2(\eta^6\text{-}p\text{-cymene})(PA)]$ complexes **5** (Scheme 4).[31]The mechanism initiates by a base-promoted loss of HCl to give the 18e rutheniumκ^2-PO-phosphinito species **A**. A transition to a κ^1 coordination frees a coordination site for the pyridine-containing substrate. At this stage, the CDM mechanism may be triggered by the phosphinito which intercepts the *ortho*-proton with a concomitant release of the chlorine atom to lead to the cationic ruthenacycle **C**.Of note, **C** corresponds to the isolated complex **9c**. According to our observations dealing



Scheme 4 Proposed mechanism for the C-H activation mediated by $[RuCl_2(\eta^6\text{-}p\text{-cymene})(PA)]$ complexes.

with reactivity of **9c** with LiCl, we believe the chlorine counterattacks the metallic center and prompts to pyridine-moiety decoordination to afford species **D**. This step might be at the origin of the observed halides effect; the counterattack is propably less favored with more bulky halides such as bromide and iodide. Finally, the rate determining oxidative addition[4d,32] occurring possiblythrough a single electron transfer process[31] and the reductive elimination give the coupling product **2** and release the complex **5**.

Conclusions

In summary, a series of $[RuCl_2(\eta^6\text{-}p\text{-cymene})]$complexes bearing phosphinous acid (PA) ligands has been straightforwardly prepared starting from the dimer $[RuCl_2(p\text{-cymene})]_2$ and secondary phosphine oxides. These complexes were fully characterized, notably by single-crystal X-ray diffraction which allowed to calculate the percent buried volumes of PAs and other phosphorus-based ligands. This quantification of the steric parameter led to a better comprehension of the coordination chemistry for this type of complexes and explained the absence of coordination in the case of bulky SPOs such as $Ad_2P(O)H$. The performances of these complexes were evaluated in C-H activation/functionalization of 2-phenylpyridine. At 80 °C, an efficient complex bearing the bulkier PA was identified. A thorough comparison of aryl halides as coupling partner revealed a sharp halide effect. Further investigations allowed to establish a halide dependence: large quantities of chlorine inhibited the C-H activation/functionalization but stoichiometric amounts were also necessary. On the basis of these results and the isolation a reaction intermediate, a mechanism involving successively the formation of κ^2-PO-

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phosphinito species, a concerted metallation deprotonation favored by the phosphinito, a chlorine counterattack and single electron transfer oxidative addition was proposed. Since the hindered $Ad_2P(O)H$ does not coordinate to the metal center even though it improves the C-H activation, we believe that it participates to the CDM as an outer-sphere base. An enantioselective version of C-H activation/functionalization taking advantage of the P-stereogenic center of PA ligands is currently under investigation in our laboratory.

Experimental

All reagents were obtained from commercial sources and used as received. Secondary phosphine oxides **4c** and **4e-g** were obtained from chemical suppliers. Other SPOs were prepared according to literature procedures: **4b**,[33] **4d**,[33] **4h**,[34] **4i**,[34] **4j**,[35] **4k**[15a] and **4l**.[34] THF was purified and dried over Braun solvent purification system (MB-SPS-800). Analytical Thin Layer Chromatography (TLC) was carried out on Merck silica gel60 F_{254}. Products were revealed by ultraviolet light (254 or 366 nm) and stained with dyeing reagents solutions. Flash chromatography was performed on Combiflash® Companion or with Merck silica gel 60 (230-400 mesh). ^{1}H, ^{13}C, ^{31}P and ^{19}F NMR spectra were recorded in $CDCl_3$ at ambient temperature on Bruker Avance III 300 or 400 spectrometers operating at 300 and 400 MHz respectively for ^{1}H. ^{13}C, ^{31}P and ^{19}F nuclei were observed with ^{1}H decoupling. Solvent residual signals were used as internal standard.[36] Chemical shifts (δ) and coupling constants (*J*) are given in ppm and Hz respectively. HRMS were recorded on SYNAPT G2 HDMS (Waters) or on QStar Elite (Applied Biosystems SGIEX) equipped with an Atmospheric Pressure Ionization (API) source. Mass spectra were obtained a Time Of Flight (TOF) analyser.X-ray Diffraction: Intensity data were collected on a Brucker-Nonius KappaCCD diffractometer using MoKα radiation (0.71073 Å) at 293(2) K. Data reduction was performed using the HKL-2000 software package. The structure was resolved using the software SIR92[37] by the direct methods and refined using SHELXL-97.[38]For compound **5d,** intensity data were collected on an Agilent SuperNova AtlasS2 diffractometer using MoKα radiation (0.71073 Å) at 293(2) K. Data reduction was performed using the CrysAlisPro software package (version 1.171.37.31). The structure was resolved using the software SHELXS-97 by the direct methods and refined using SHELXL-2013-4. The CIF files of compounds **5b-d**, **5h**, **5i**, **5k** and **5l** have been deposited with CCDC numbers 1434226-1434232, respectively.

General procedure for the synthesis of complexes [RuCl$_2$(*η*^{6}-arene)(PA)]5. In a Schlenk flask, a solution of ruthenium dimer [RuCl$_2$(η^6-*p*-cymene)]$_2$ (61.2 mg, 0.1 mmol, 2 equiv. of ruthenium) and secondary phosphine oxide (0.22 mmol, 2.2 equiv.) in THF (2 mL) was stirred at room temperature for 3 h. The reaction mixture was half-concentrated and *n*-hexane (10 mL) was added to initiate a precipitation. The red precipitate was filtered off and washed with *n*-hexane. Recrystallisation from DCM/*n*-hexane gave crystals of the desired product.

[RuCl$_2$(η^6-*p*-cymene)(Cy$_2$POH)] 5b. According to the general procedure, complex **5b** was obtained after 24 h of reaction as a red solid (92 mg, 89%). ^{1}H NMR (400 MHz, $CDCl_3$):δ (ppm) = 5.59 (d, *J*(H,H) = 6.0 Hz, 2H, H^{Ar}), 5.56 (d, *J*(H,H) = 6.0 Hz, 2H, H^{Ar}), 5.13 (br. s, 1H, PO-*H*), 2.81 (sept, *J*(H,H) = 6.9 Hz, 1H, C*H*(CH$_3$)$_2$), 2.40-1.20 (m, 22H, C*H*$_2$ and C*H*), 2.10 (s, 3H, C-C*H*$_3$), 1.28 (d, *J*(H,H) = 7.0 Hz, 6H, CH(C*H*$_3$)$_2$). ^{13}C NMR (101 MHz, $CDCl_3$):δ (ppm) = 107.8 (C^{Ar}), 94.1 (C^{Ar}), 89.0 (C^{Ar}-H), 84.5 (C^{Ar}-H), 42.9 (CH, C-P), 30.9 (CH), 27.8-25.8 (10 CH$_2$), 22.3 (CH$_3$), 18.3 (CH$_3$). ^{31}P{^{1}H} NMR (162 MHz, $CDCl_3$): δ (ppm) = 129.3 (s). HRMS (ESI+): m/z: calcd for $C_{22}H_{37}Cl_2NaOPRu$: 543.0895 [M+Na]$^+$; found: 543.0898.

[RuCl$_2$(η^6-*p*-cymene)(Ph$_2$POH)]5c. According to the general procedure, complex **5c** was obtained as a red solid (97 mg, 96%). ^{1}H NMR (400 MHz, $CDCl_3$):δ (ppm) = 7.75-7.65 (m, 4H, H^{Ar}), 7.55-7.40 (m, 6H, H^{Ar}), 5.40 (d, *J*(H,H) = 5.9 Hz, 2H, H^{Ar}), 5.26 (d, *J*(H,H) = 6.0 Hz, 2H, H^{Ar}), 2.51 (sept, *J*(H,H) = 6.9 Hz, 1H, C*H*(CH$_3$)$_2$), 2.01 (s, 3H, C-C*H*$_3$), 0.98 (d, *J*(H,H) = 7.0 Hz, 6H, CH(C*H*$_3$)$_2$). ^{13}C NMR (101 MHz, $CDCl_3$):δ (ppm) = 137.5 (C^{Ar}-P), 131.7 (C^{Ar}-H), 131.3 (C^{Ar}-H), 128.4 (C^{Ar}-H), 108.8 (C^{Ar}), 96.8 (C^{Ar}), 89.7 (C^{Ar}-H), 87.0 (C^{Ar}-H), 30.4 (CH), 21.9 (CH$_3$), 17.9 (CH$_3$). ^{31}P{^{1}H} NMR (162 MHz, $CDCl_3$):δ (ppm) = 107.0 (s). HRMS (ESI+): m/z: calcd for $C_{22}H_{25}Cl_2NaOPRu$: 530.9956 [M+Na]$^+$; found: 530.9957.

[RuCl$_2$(η^6-*p*-cymene)((*p*-F-C$_6$H$_5$)$_2$POH)]5d. According to the general procedure, complex **5d** was obtained after 6 h of reaction as a red solid (92 mg, 84%). ^{1}H NMR (300 MHz, $CDCl_3$): δ (ppm) = 7.75-7.65 (m, 4H, H^{Ar}), 7.20-7.10 (m, 4H, H^{Ar}), 5.38 (d, *J*(H,H) = 5.7 Hz, 2H, H^{Ar}), 5.27 (d, *J*(H,H) = 5.8 Hz, 2H, H^{Ar}), 2.54 (sept, *J*(H,H) = 7.0 Hz, 1H, C*H*(CH$_3$)$_2$), 2.00 (s, 3H, C-C*H*$_3$), 1.01 (d, *J*(H,H) = 6.9 Hz, 6H, CH(C*H*$_3$)$_2$). ^{13}C NMR (75 MHz, $CDCl_3$): δ (ppm) = 164.1 (C-F), 134.1 (C^{Ar}-H), 133.2 (C^{Ar}-P), 115.7 (C^{Ar}-H), 109.3 (C^{Ar}), 97.1 (C^{Ar}), 88.7 (C^{Ar}-H), 87.1 (C^{Ar}-H), 30.6 (CH), 21.7 (CH$_3$), 18.0 (CH$_3$). ^{19}F{^{1}H} NMR (377 MHz, $CDCl_3$): δ (ppm) = -107.6 (s). ^{31}P{^{1}H} NMR (121 MHz, $CDCl_3$): δ (ppm) = 105.7 (s). HRMS (ESI-): m/z: calcd for $C_{22}H_{22}Cl_2OPRu$: 542.9803 [M-H]$^-$; found: 542.9792.

[RuCl$_2$(η^6-*p*-cymene)((3,5-Me$_2$-C$_6$H$_3$)$_2$POH)]5e. According to the general procedure, complex **5e** was obtained as a red solid (103 mg, 91%). ^{1}H NMR (300 MHz, $CDCl_3$): δ (ppm) = 7.30 (d, *J*(H,P) = 11.4 Hz, 4H, H^{Ar}), 7.10 (s, 2H, H^{Ar}), 6.51 (br. s, 1H, PO-*H*), 5.40 (d, *J*(H,H) = 5.8 Hz, 2H, H^{Ar}), 5.18 (d, *J*(H,H) = 5.8 Hz, 2H, H^{Ar}), 2.56 (sept, *J*(H,H) = 6.9 Hz, 1H, C*H*(CH$_3$)$_2$), 2.35 (s, 12H, C-C*H*$_3$), 2.06 (s, 3H, C-C*H*$_3$), 0.98 (d, *J*(H,H) = 7.0 Hz, 6H, CH(C*H*$_3$)$_2$). ^{13}C NMR (101 MHz, $CDCl_3$):δ (ppm) = 137.8 (C^{Ar}), 137.7 (C^{Ar}), 137.3 (C^{Ar}), 136.7 (C^{Ar}), 132.82 (C^{Ar}-H), 132.80 (C^{Ar}-H), 129.1 (C^{Ar}-H), 129.0 (C^{Ar}-H), 107.9 (C^{Ar}), 95.3 (C^{Ar}), 90.21 (C^{Ar}-H), 90.16 (C^{Ar}-H), 87.72 (C^{Ar}-H), 88.66 (C^{Ar}-H), 30.3 (CH), 21.6 (CH$_3$), 21.4 (CH$_3$), 17.7 (CH$_3$).^{31}P{^{1}H} NMR (121 MHz, $CDCl_3$): δ (ppm) = 105.7 (s).HRMS (ESI-): m/z: calcd for $C_{26}H_{32}Cl_2NaOPRu$: 563.0618 [M-H]$^+$; found: 563.0620.

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[RuCl$_2$(η^6-*p*-cymene)(MePhPOH)] 5h.According to the general procedure, complex **5h** was obtained as a red solid (63 mg, 71%).^{1}H NMR (400 MHz, CDCl$_3$):δ (ppm) = 7.80-7.70 (m, 2H, *H*^{Ar}), 7.60-7.50 (m, 3H, *H*^{Ar}), 6.15 (br. s, 1H, PO-*H*), 5.24 (d, *J*(H,H) = 6.3 Hz, 1H, *H*^{Ar}), 5.21 (d, *J*(H,H) = 5.8 Hz, 1H, *H*^{Ar}), 5.08 (d, *J*(H,H) = 5.8 Hz, 1H, *H*^{Ar}), 5.04 (d, *J*(H,H) = 6.1 Hz, 1H, *H*^{Ar}), 2.65 (sept, *J*(H,H) = 6.9 Hz, 1H, C*H*(CH$_3$)$_2$), 2.12 (d, *J*(H,P) = 10.0 Hz, 3H, P-C*H*$_3$), 1.94 (s, 3H, C-C*H*$_3$), 1.13 (d, *J*(H,H) = 7.0 Hz, 3H, CH(C*H*$_3$)$_2$), 1.04 (d, *J*(H,H) = 7.0 Hz, 3H, C*H*(C*H*$_3$)$_2$). ^{13}C NMR (101 MHz, CDCl$_3$): δ (ppm) = 140.9 (C^{Ar}-P), 131.1 (C^{Ar}-H), 128.9 (C^{Ar}-H), 128.8 (C^{Ar}-H), 107.6 (C^{Ar}), 96.1 (C^{Ar}), 91.3 (C^{Ar}-H), 89.3 (C^{Ar}-H), 87.6 (C^{Ar}-H), 86.1 (C^{Ar}-H), 30.5 (CH), 22.2 (CH$_3$), 21.9 (CH$_3$), 18.7 (CH$_3$), 18.3 (CH$_3$). ^{31}P{^{1}H} NMR (162 MHz, CDCl$_3$): δ (ppm) = 109.5 (s). HRMS (ESI+): m/z: calcd for C$_{17}$H$_{23}$Cl$_2$NaOPRu: 468.9798 [M+Na]$^+$; found: 468.9806.

[RuCl$_2$(η^6-*p*-cymene)(*n*BuPhPOH)] 5i.According to the general procedure, complex **5i** was obtained as a red solid (51 mg, 53%).^{1}H NMR (400 MHz, CDCl$_3$): δ (ppm) = 7.80-7.70 (m, 2H, *H*^{Ar}), 7.60-7.45 (m, 3H, *H*^{Ar}), 5.26 (d, *J*(H,H) = 6.0 Hz, 1H, *H*^{Ar}), 5.18 (d, *J*(H,H) = 5.8 Hz, 1H, *H*^{Ar}), 5.14 (d, *J*(H,H) = 6.0 Hz, 1H, *H*^{Ar}), 5.05 (d, *J*(H,H) = 5.8 Hz, 1H, *H*^{Ar}), 2.80-2.65 (m, 1H, C*H*$_2$), 2.61 (sept, *J*(H,H) = 7.0 Hz, 1H, C*H*(CH$_3$)$_2$), 2.25-2.10 (m, 1H, C*H*$_2$), 1.91 (s, 3H, C-C*H*$_3$), 1.65-1.15 (m, 4H, C*H*$_2$), 1.11 (d, *J*(H,H) = 7.0 Hz, 3H, CH(C*H*$_3$)$_2$), 0.97 (d, *J*(H,H) = 7.0 Hz, 3H, CH(C*H*$_3$)$_2$), 0.97 (t, *J*(H,H) = 7.0 Hz, 3H, CH$_2$-C*H*$_3$). ^{13}C NMR (101 MHz, CDCl$_3$): δ (ppm) = 138.5 (C^{Ar}-P), 130.8 (C^{Ar}-H), 129.2 (C^{Ar}-H), 128.9 (C^{Ar}-H), 107.4 (C^{Ar}), 95.7 (C^{Ar}), 92.2 (C^{Ar}-H), 88.8 (C^{Ar}-H), 87.0 (C^{Ar}-H), 86.8 (C^{Ar}-H), 31.4 (CH$_2$), 30.4 (CH), 24.6 (CH$_2$), 24.0 (CH$_2$), 22.2 (CH$_3$), 21.6 (CH$_3$), 18.2 (CH$_3$), 13.8 (CH$_3$). ^{31}P{^{1}H} NMR (162 MHz, CDCl$_3$): δ (ppm) = 113.1 (s). HRMS (ESI+): m/z: calcd for C$_{20}$H$_{29}$Cl$_2$NaOPRu: 511.0268 [M+Na]$^+$; found: 511.0270.

[RuCl$_2$(η^6-*p*-cymene)(BnPhPOH)] 5j. According to the general procedure, complex **5j** was obtained as a deep-red solid (92 mg, 88%).^{1}H NMR (300 MHz, CDCl$_3$): δ (ppm) = 7.70-7.60 (m, 2H, *H*^{Ar}), 7.50-7.40 (m, 3H, *H*^{Ar}), 7.10-7.00 (m, 3H, *H*^{Ar}), 6.85-6.75 (m, 2H, *H*^{Ar}), 5.30-5.15 (m, 3H, *H*^{Ar}), 5.10 (d, ^{3}*J*(H,H) = 5.9 Hz, 1H, *H*^{Ar}), 4.01 (m, 1H, C*H*$_2$-P), 3.54 (d, ^{2}*J*(H,P) = 15.2 Hz, 1H, C*H*$_2$-P), 2.70 (sept, ^{3}*J*(H,H) = 6.9 Hz, 1H, C*H*(CH$_3$)$_2$), 1.97 (s, 3H, C-C*H*$_3$), 1.16 (d, ^{3}*J*(H,H) = 6.9 Hz, 3H, CH(C*H*$_3$)$_2$), 1.07 (d, ^{3}*J*(H,H) = 6.9 Hz, 3H, CH(C*H*$_3$)$_2$). ^{13}C NMR (101 MHz, CDCl$_3$): δ (ppm) = 136.4 (C^{Ar}-P), 133.7 (C^{Ar}), 131.0 (C^{Ar}-H), 130.5 (C^{Ar}-H), 129.7 (C^{Ar}-H), 128.5 (C^{Ar}-H), 128.0 (C^{Ar}-H), 126.4 (C^{Ar}-H), 108.7 (C^{Ar}), 97.4 (C^{Ar}), 91.3 (C^{Ar}-H), 88.3 (C^{Ar}-H), 87.5 (C^{Ar}-H), 87.1 (C^{Ar}-H), 38.9 (CH$_2$), 30.4 (CH), 22.3 (CH$_3$), 21.7 (CH$_3$), 18.3 (CH$_3$). ^{31}P{^{1}H} NMR (121 MHz, CDCl$_3$): δ (ppm) = 109.3 (s). HRMS (ESI+): m/z: calcd for C$_{23}$H$_{27}$Cl$_2$NaOPRu: 545.0113 [M+Na]$^+$; found: 545.0101.

[RuCl$_2$(η^6-*p*-cymene)(CyPhPOH)] 5k. According to the general procedure, complex **5k** was obtained as a red solid (100 mg, 98%).^{1}H NMR (400 MHz, CDCl$_3$): δ (ppm) = 7.75-7.65 (m, 2H, *H*^{Ar}), 7.55-7.45 (m, 3H, *H*^{Ar}), 5.52 (d, *J*(H,H) = 6.5 Hz, 1H, *H*^{Ar}), 5.48 (d, *J*(H,H) = 6.5 Hz, 1H, *H*^{Ar}), 5.19 (d, *J*(H,H) = 5.5 Hz, 1H, *H*^{Ar}), 4.90 (d, *J*(H,H) = 5.5 Hz, 1H, *H*^{Ar}), 2.58 (sept, *J*(H,H) = 6.9 Hz, 1H, C*H*(CH$_3$)$_2$), 2.50-2.20 (m, 2H, C*H* and C*H*$_2$), 1.99 (s, 3H, C-C*H*$_3$), 1.90-1.10 (m, 9H, C*H*$_2$), 1.10 (d, *J*(H,H) = 7.0 Hz, 3H, CH(C*H*$_3$)$_2$), 0.75 (d, *J*(H,H) = 7.0 Hz, 3H, CH(C*H*$_3$)$_2$). ^{13}C NMR (101 MHz, CDCl$_3$): δ (ppm) = 137.5 (C^{Ar}-P), 129.4 (C^{Ar}-H), 128.4 (C^{Ar}-H), 127.3 (C^{Ar}-H), 105.6 (C^{Ar}), 94.5 (C^{Ar}), 93.4 (C^{Ar}-H), 89.3 (C^{Ar}-H), 84.3 (C^{Ar}-H), 82.7 (C^{Ar}-H), 41.2 (*C*H-P), 29.2 (CH), 26.0-25.0 (5 CH$_2$), 21.9 (CH$_3$), 19.2 (CH$_3$), 17.0 (CH$_3$). ^{31}P{^{1}H} NMR (162 MHz, CDCl$_3$): δ (ppm) = 114.2 (s). HRMS (ESI+): m/z: calcd for C$_{22}$H$_{31}$Cl$_2$NaOPRu: 537.0426 [M+Na]$^+$; found: 537.0421.

[RuCl$_2$(η^6-*p*-cymene)(*t*BuPhPOH)] 5l.According to the general procedure, complex **5l** was obtained as a deep-red solid (97 mg, 99%).^{1}H NMR (400 MHz, CDCl$_3$): δ (ppm) = 7.80-7.70 (m, 2H, *H*^{Ar}), 7.55-7.45 (m, 3H, *H*^{Ar}), 6.20 (br. s, 1H, PO-*H*), 5.48 (d, *J*(H,H) = 5.9 Hz, 1H, *H*^{Ar}), 5.39 (d, *J*(H,H) = 6.3 Hz, 1H, *H*^{Ar}), 5.35 (d, *J*(H,H) = 6.3 Hz, 1H, *H*^{Ar}), 5.15 (d, *J*(H,H) = 6.0 Hz, 1H, *H*^{Ar}), 2.78 (sept, *J*(H,H) = 7.0 Hz, 1H, C*H*(CH$_3$)$_2$), 2.01 (s, 3H, C-C*H*$_3$), 1.21 (d, *J*(H,P) = 15.0 Hz, 9H, C(C*H*$_3$)$_3$), 1.18 (d, *J*(H,H) = 7.0 Hz, 3H, CH(C*H*$_3$)$_2$), 1.01 (d, *J*(H,H) = 7.0 Hz, 3H, CH(C*H*$_3$)$_2$). ^{13}C NMR (101 MHz, CDCl$_3$): δ (ppm) = 137.1 (C^{Ar}-P), 130.4 (C^{Ar}-H), 130.0 (C^{Ar}-H), 128.0 (C^{Ar}-H), 107.6 (C^{Ar}), 94.2 (C^{Ar}), 92.3 (C^{Ar}-H), 90.5 (C^{Ar}-H), 86.6 (C^{Ar}-H), 86.1 (C^{Ar}-H), 39.9 (C), 30.4 (CH), 26.3 (CH$_3$), 22.0 (CH$_3$), 21.7 (CH$_3$), 18.0 (CH$_3$). ^{31}P{^{1}H} NMR (162 MHz, CDCl$_3$): δ (ppm) = 115.1 (s). HRMS (ESI+): m/z: calcd for C$_{20}$H$_{29}$Cl$_2$NaOPRu: 511.0268 [M+Na]$^+$; found: 511.0272.

[RuBr$_2$(η^6-*p*-cymene)(*t*BuPhPOH)] 6l. According to the general procedure using dimer [RuBr$_2$(η^6-*p*-cymene)]$_2$, complex **6l** was obtained as a deep-red solid (94 mg, 81%). ^{1}H NMR (300 MHz, CDCl$_3$): δ (ppm) = 7.80-7.60 (m, 2H, *H*^{Ar}), 7.55-7.40 (m, 3H, *H*^{Ar}), 5.55 (d, *J*(H,H) = 6.1 Hz, 1H, H^{Ar}), 5.52 (br. s, 1H, PO-*H*), 5.41 (d, *J*(H,H) = 6.1 Hz, 1H, *H*^{Ar}), 5.37 (d, *J*(H,H) = 6.2 Hz, 1H, *H*^{Ar}), 5.27 (d, *J*(H,H) = 6.2 Hz, 1H, *H*^{Ar}), 2.93 (sept, *J*(H,H) = 7.0 Hz, 1H, C*H*(CH$_3$)$_2$), 2.08 (s, 3H, C-C*H*$_3$), 1.23 (d, *J*(H,P) = 15.0 Hz, 9H, C(C*H*$_3$)$_3$), 1.20 (d, *J*(H,H) = 7.0 Hz, 3H, CH(C*H*$_3$)$_2$), 1.04 (d, *J*(H,H) = 7.0 Hz, 3H, CH(C*H*$_3$)$_2$). ^{13}C NMR (75 MHz, CDCl$_3$): δ (ppm) = 137.6 (C^{Ar}-P), 130.3 (3 C^{Ar}-H), 127.8 (2 C^{Ar}-H), 109.6 (C^{Ar}), 94.3 (C^{Ar}), 91.8 (C^{Ar}-H), 91.2 (C^{Ar}-H), 86.6 (C^{Ar}-H), 85.0 (C^{Ar}-H), 40.7 (C), 31.1 (CH), 26.6 (CH$_3$), 22.2 (CH$_3$), 22.1 (CH$_3$), 18.7 (CH$_3$). ^{31}P{^{1}H} NMR (121 MHz, CDCl$_3$): δ (ppm) = 113.3 (s). HRMS (ESI+): m/z: calcd for C$_{20}$H$_{29}$Br$_2$NaOPRu: 600.9246 [M+Na]$^+$; found: 600.9247.

[RuI$_2$(η^6-*p*-cymene)(*t*BuPhPOH)] 7l.According to the general procedure using dimer [RuI$_2$(η^6-*p*-cymene)]$_2$, complex **7l** was obtained as a deep-red solid (121 mg, 90%).^{1}H NMR (300 MHz, CDCl$_3$): δ (ppm) = 7.70-7.60 (m, 2H, *H*^{Ar}), 7.50-7.40 (m, 3H, *H*^{Ar}), 5.71 (d, *J*(H,H) = 6.2 Hz, 1H, *H*^{Ar}), 5.54 (d, *J*(H,H) = 6.1 Hz, 1H, *H*^{Ar}), 5.43 (d, *J*(H,H) = 6.1 Hz, 1H, *H*^{Ar}), 5.39 (d, *J*(H,H) = 6.3 Hz, 1H, *H*^{Ar}), 4.72 (br. s, 1H, PO-*H*), 3.21 (sept, *J*(H,H) = 7.0 Hz, 1H, C*H*(CH$_3$)$_2$), 2.22 (s, 3H, C-C*H*$_3$), 1.24 (d, *J*(H,P) = 14.8 Hz, 9H, C(C*H*$_3$)$_3$), 1.23 (d, *J*(H,H) = 7.0 Hz, 3H, CH(C*H*$_3$)$_2$), 1.08 (d, *J*(H,H) = 7.0 Hz, 3H, CH(C*H*$_3$)$_2$). ^{13}C NMR (75 MHz, CDCl$_3$): δ (ppm) = 138.9 (C^{Ar}-P), 130.6 (C^{Ar}-H), 130.1 (C^{Ar}-H), 127.5 (C^{Ar}-H), 112.9 (C^{Ar}), 95.5 (C^{Ar}), 92.8 (C^{Ar}-H), 89.8 (C^{Ar}-H), 86.3 (C^{Ar}-H), 84.0 (C^{Ar}-H), 41.3 (C), 32.4 (CH), 27.2 (CH$_3$), 23.1 (CH$_3$), 22.2 (CH$_3$),

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19.9 (CH_3). $^{31}P\{^1H\}$ NMR (162 MHz, $CDCl_3$): δ (ppm) = 113.9 (s). HRMS (ESI+): m/z: calcd for $C_{20}H_{29}I_2KOPRu$: 710.8726 $[M+K]^+$; found: 710.8737.

[Ru(η^6-*p*-cymene)(Ph_2POH)(2-phenylpyridine-κ^2-NC)BF_4] 9c. In a round-bottomed flask, were introduced in turn $AgBF_4$ (56 mg, 0.29 mmol), ruthenacycle **8** (122 mg, 0.29 mmmol), Ph_2PHO (58 mg, 0.29 mmol) and 5 mL of dry DCM. The reaction mixture was stirred at room temperature for 1h and filtered on Celite®. Volatiles removed to afford complex **9c** as brown-grey solid (194 mg, 99%). ^{1}H NMR (400 MHz, $CDCl_3$):δ (ppm) = 9.27 (d, *J*(H,H) = 5.4 Hz, 1H, H^{Ar}), 8.09 (d, *J*(H,H) = 7.7 Hz, 1H, H^{Ar}), 7.60-7.55 (m, 2H, H^{Ar}), 7.50 (td, *J*(H,H) = 7.7 and 1.1 Hz, 1H, H^{Ar}), 7.36-7.29 (m, 3H, H^{Ar}), 7.26-7.20 (m, 3H, H^{Ar}), 7.16 (d, *J*(H,H) = 8.2 Hz, 1H, H^{Ar}), 7.06 (t, *J*(H,H) = 7.7 Hz, 1H, H^{Ar}), 7.03-6.99 (m, 1H, H^{Ar}), 6.78 (dt, *J*(H,H) = 8.0 and 2.6 Hz, 2H, H^{Ar}), 6.50 (dd, *J*(H,H) = 8.4 and 1.2 Hz, 1H, H^{Ar}), 6.47 (dd, *J*(H,H) = 8.2 and 1.0 Hz, 1H, H^{Ar}), 6.40 (d, *J*(H,H) = 6.4 Hz, 1H, H^{Ar}), 6.05 (dd, *J*(H,H) = 6.4 and 1.4 Hz, 1H, H^{Ar}), 5.86 (dd, *J*(H,H) = 6.1 and 1.2 Hz, 1H, H^{Ar}), 5.33 (d, *J*(H,H) = 6.0 Hz, 1H, H^{Ar}), 2.24 (sept, *J*(H,H) = 6.9 Hz, 1H, $CH(CH_3)_2$), 1.88 (s, 3H, C-CH_3), 0.80 (d, *J*(H,H) = 6.9 Hz, 3H, $CH(CH_3)_2$), 0.72 (d, *J*(H,H) = 6.9 Hz, 3H, $CH(CH_3)_2$). ^{13}C NMR (101 MHz, $CDCl_3$):δ (ppm) = 171.5 (C^{Ar}), 171.3 (C^{Ar}), 165.0 (C^{Ar}), 156.49 (C^{Ar}-H), 156.47 (C^{Ar}-H), 144.9 (C^{Ar}), 141.54 (C^{Ar}-H), 141.51 (C^{Ar}-H), 137.0 (C^{Ar}-H), 136.6 (C^{Ar}), 136.0 (C^{Ar}), 132.5 (C^{Ar}), 134.7 (C^{Ar}), 130.3 (C^{Ar}-H), 130.2 (C^{Ar}-H), 130.1 (C^{Ar}-H), 130.0 (C^{Ar}-H), 129.37 (C^{Ar}-H), 129.35 (C^{Ar}-H), 129.2 (C^{Ar}-H), 129.1 (C^{Ar}-H), 129.0 (C^{Ar}-H), 127.8 (C^{Ar}-H), 127.7 (C^{Ar}-H), 127.5 (C^{Ar}-H), 127.3 (C^{Ar}-H), 125.0 (C^{Ar}-H), 123.1 (C^{Ar}-H), 122.5 (C^{Ar}-H), 119.3 (C^{Ar}-H), 113.5 (C^{Ar}), 113.4 (C^{Ar}), 108.5 (C^{Ar}), 96.61 (C^{Ar}-H), 96.59 (C^{Ar}-H), 96.56 (C^{Ar}-H), 96.4 (C^{Ar}-H), 85.3 (C^{Ar}-H), 31.0 (CH), 22.2 (CH_3), 22.2 (CH_3), 18.8 (CH_3). $^{31}P\{^1H\}$ NMR (162 MHz, $CDCl_3$):δ (ppm) = 114.7 (s). ^{19}F NMR (376 MHz, $CDCl_3$):δ (ppm) = -150.5 (s). HRMS (ESI+): m/z: calcd for $C_{33}H_{33}NOPRu$: 592.1347 $[M-BF_4]^+$; found: 592.1345.

Acknowledgements

This work was supported by the Ministère de l'enseignement supérieur et de la recherche (L.G. Ph.D. grant), the CNRS, AMU, and Centrale Marseille. Dr. Valérie Monnier and Christophe Chendo (Spectropole, Fédération des Sciences Chimiques de Marseille) are gratefully acknowledged for MS analyses We thank Matthieu Ortega for the preparation of SPOs, Dr. Alphonse Tenaglia for fruitful discussions and Dr. Julie Broggi for useful comments on the manuscript.We are indebted to both referees for relevant comments and suggestions.

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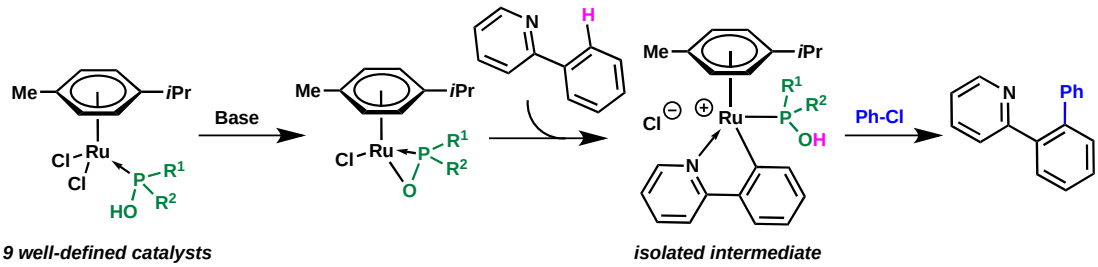

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