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Ruthenium Complexes of κ(P)- and κ(P)-η⁶-Coordinated KITPHOS Monophosphines: Efficient Catalysts for the Direct Ortho Arylation of 2-Phenylpyridine and *N*-Phenylpyrazole with Aryl Chlorides

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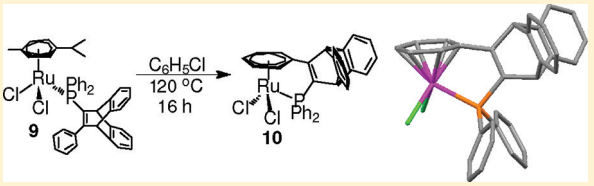
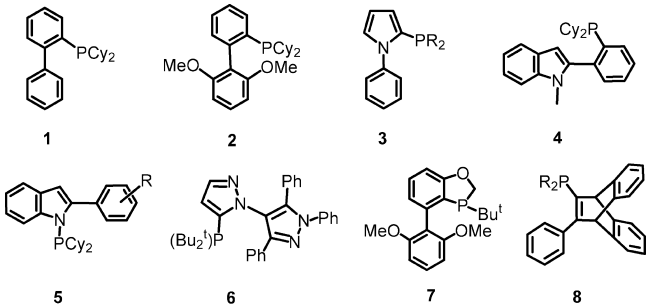
Supporting Information

ABSTRACT: Thermolysis of the P-coordinated KITPHOS monophosphine complex [(*p*-cymene)$RuCl_2$(KITPHOS)] in chlorobenzene at 120 °C resulted in displacement of the *p*-cymene to afford [{κ(*P*)-η⁶-KITPHOS}$RuCl_2$], the first example of a constrained-geometry complex in which the κ(P)-bonded diphenylphosphino group and the η⁶-coordinated proximal phenyl ring are connected by an unsaturated two-carbon tether; both complexes form efficient catalysts for the direct ortho arylation of 2-phenylpyridine and *N*-phenylpyrazole with a range of aryl chlorides.



Arguably, since their introduction electron-rich biaryl monophosphines such as **1** and **2** have evolved into one of the most versatile and efficient classes of ligand for transition-metal-catalyzed C−C and C−heteroatom bond formation; examples include Suzuki−Miyaura,[1] Negishi,[2] and Hiyama[3] cross couplings and Buchwald−Hartwig amination,[4] borylation,[5] silylation,[6] etherification,[7] and direct arylation[8] as well as a diverse range of gold-catalyzed cyclizations and cycloisomeriszations.[9] The biaryl framework appears to be integral to the success of these ligands and as such has been used as a lead architecture for developing alternative systems such as *cataCXium* P-ligand **3**,[10] indolyl-based monophosphines **4** and **5**,[11] BippyPhos **6**,[12] and most recently BI-DIME **7**.[13] Interestingly though, a PPh_2-based biaryl-like phosphine has recently been reported to outperform its bulkier, electron-rich counterpart for a host of challenging cross couplings,[14] and electron-deficient triarylphosphines have been reported to be highly effective ligands for the direct arylation of heterocycles with aryl iodides, substrates that had proven to be particularly unreactive under broadly applicable conditions.[15] These examples should encourage further investigations to explore and develop the use of bulky electron-deficient phosphines in palladium-catalyzed transformations.



We have also embraced this basic design concept and recently introduced a new class of electron-rich biaryl-like KITPHOS monophosphine (**8**),[16] which bears a close architectural similarity to Buchwald's biaryl monophosphines in that there is a PR_2 group connected to a carbon−carbon double bond, albeit part of an anthracene-derived bicyclic framework, and a non-phosphine-containing proximal aryl ring, which can be systematically modified as it is derived from a 1-alkynylphosphine oxide. Gratifyingly, in addition to being an architectural analogue, electron-rich KITPHOS monophosphines either rivaled or outperformed their biaryl-based counterparts in palladium-catalyzed Suzuki−Miyaura and Buchwald−Hartwig cross couplings[16] as well as a host of gold-catalyzed intramolecular cyclizations.[17] The latter studies also revealed that electrophilic gold(I) complexes of diphenylphosphino-based KITPHOS monophosphines were more efficient than their dicyclohexyl-based counterparts for the 5-exo-dig cycloisomerization of a range of propargyl amides, to afford the corresponding alkylidene oxazolines.[17a] Extending this analogy further, diphenylphosphino-substituted KITPHOS monophosphines would be potential surrogates for PPh_2-based biaryl monophosphines, a class of ligand that has received far less attention than its dialkylphosphino counterpart (vide supra), primarily because they are less electron-rich and lack steric bulk, properties that are commonly considered necessary to achieve efficient palladium-catalyzed C−C and C−heteroatom bond formation.

Interested in exploring the extent to which diphenylphosphino-based KITPHOS monophosphines could be surrogates for conventional biaryl-like or triaryl monophosphines, we have been investigating their ruthenium-based coordination chem-

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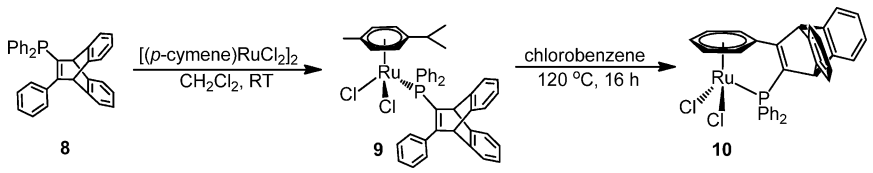
Scheme 1



istry relevant to the direct arylation of (hetero)arenes and discovered that the KITPHOS monophosphine **8** (R = Ph, PPh_2-(Ph)-KITPHOS) can coordinate either in a conventional κ(P) manner or as a κ(P)-η^6 eight-electron donor, tethered through the proximal phenyl ring of the biaryl-like fragment to form a constrained-geometry complex and that both form efficient catalysts for the direct ortho arylation of 2-phenylpyridine and *N*-phenylpyrazole. To this end, the ruthenium-catalyzed arylation and alkylation of 2-aryl-substituted hetero(arenes) is rapidly emerging as a powerful and synthetically versatile tool for C−H bond functionalization.[18] While early developments in this area involved ruthenium−arene precatalysts based on triphenylphosphine,[19] air-stable secondary phosphine oxides,[20] electron-rich biaryl monophosphines,[21] N-heterocyclic carbene-tethered arenes,[22] and alkylidenes[23] have proven to be efficient ligands for direct arylation and more recently well-defined ligand-free carboxylato ruthenium(II) systems have been shown to be competent catalysts; these latter systems appear to operate via a concerted carboxylate-assisted C−H activation.[24]

RESULTS AND DISCUSSION

Addition of the KITPHOS monophosphine **8** (R = Ph) to a dichloromethane solution of $[(p\text{-cymene})RuCl_2]_2$[25] resulted in cleavage of the dimer to afford $[(p\text{-cymene})Ru\{PPh_2\text{-(Ph)-KITPHOS}\}Cl_2]$ (**9**), which was isolated in near-quantitative yield as a pale orange solid (Scheme 1). Although ^{31}P, ^{1}H, and ^{13}C NMR spectra, the electrospray mass spectrum, and analytical data were all consistent with κ(P) coordination of the KITPHOS monophosphine, the identity of **9** was conclusively established by a single-crystal X-ray study; a perspective view of the molecular structure is shown in Figure 1.

Figure 1 clearly shows that the ruthenium atom adopts a pseudo-octahedral geometry with the *p*-cymene, two chloride ligands, and the κ(*P*)-KITPHOS monophosphine completing the coordination sphere. The Ru−C(arene) bond lengths fall between 2.144(3) and 2.243(3) Å, and the range of Ru−C(arene) distances of 2.145(2)−2.242(2) Å is within the range reported for related complexes such as $[(p\text{-cymene})Ru(PPh_2py)Cl_2]$ (2.214(2) Å),[26] $[(p\text{-cymene})Ru(PPh_2H)Cl_2]$ (2.198(4) Å),[26] $[(p\text{-cymene})Ru(dppv)Cl_2]$ (2.21(3) Å),[27] and $[(p\text{-cymene})Ru(PPh_3)Cl_2]$ (2.218(2) Å).[28] The Ru(1)−P(1) bond length of 2.3527(6) Å is unexceptional and is similar to those in $[(p\text{-cymene})Ru\{o\text{-(diphenylphosphino)aniline}\}Cl_2]$ (2.376(2) Å),[29] $[(p\text{-cymene})Ru(PPh_3)Cl_2]$ (2.3438(6) Å),[28] and $[(p\text{-cymene})Ru\{(1,2\text{-diphenylvinyl})\text{-diphenylphosphine}\}Cl_2]$ (2.3632(11) Å)[30] as are the Ru(1)−Cl(1) and Ru(1)−Cl(2) bond lengths of 2.4038(6) and 2.4106(6) Å, respectively. The Cl(1)−Ru(1)−Cl(2) angle of 89.60(2)° and the P(1)−Ru(1)−Cl(1) and P(1)−Ru(1)−Cl(2) angles of 87.08(2) and 89.34(2)°, respectively, are close to those in $[(p\text{-cymene})Ru\{(1,2\text{-diphenylvinyl})\text{-diphenylphosphine}\}Cl_2]$,[30] suggesting a similar steric environment at ruthenium. The *p*-cymene ring is essentially planar with maximum and mean deviations from the least-squares mean plane of the six carbon atoms of 0.0137(18) and −0.0028(19) Å, respectively.

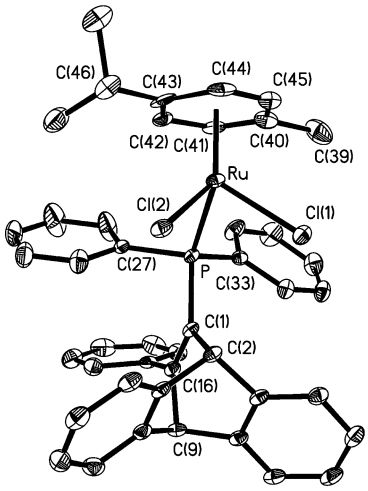


Figure 1. Molecular structure of $[(p\text{-cymene})Ru(\kappa(P)\text{-}\{11\text{-(diphenylphosphino)-12-phenyl-9,10-dihydro-9,10-ethanoanthracene}\})Cl_2]$ (**9**). Hydrogen atoms and the chloroform molecule of crystallization have been omitted for clarity. Ellipsoids are at the 40% probability level.

Interestingly, the ^{31}P NMR spectrum of the solution isolated after crystallization of **9** contained two signals, one at δ 23.9 corresponding to **9** and a low-field signal at δ 49.6, which was not present prior to crystallization. Reasoning that **9** was slowly interconverting to a thermodynamically more stable product, a chlorobenzene solution was heated at 120 °C for approximately 16 h; after this time analysis of the reaction mixture by ^{31}P NMR spectroscopy revealed that **9** had cleanly and quantitatively converted into a single product, **10**, corresponding to the species at δ 49.6. Our formulation that **10** was the product of an intramolecular displacement of the *p*-cymene fragment by the proximal phenyl ring of the KITPHOS monophosphine was initially based on the absence of any distinctive signals associated with the methyl and methine groups of the *p*-cymene together with three high-field multiplets, a triplet of doublets at δ 6.30, a triplet at δ 6.05, and a doublet at δ 4.98, which are diagnostic of the η^6-coordinated proximal phenyl ring of the biaryl-like fragment; two additional doublets at δ 5.44 and 5.13, each of intensity 1H, belong to the protons attached to the bridgehead carbon atoms of the bicyclic framework. A single-crystal X-ray structure determination of **10** was undertaken in order to unequivocally establish its identity and to determine the influence of κ(P)-η^6 coordination on the metal−phosphine bonding as well as the coordination geometry at the metal, by comparison with related systems. A perspective view of the molecular structure of **10** is shown in Figure 2. The molecular structure shows that the ruthenium atom adopts the expected three-legged piano-stool coordination and confirms that **8a** is coordinated as an eight-

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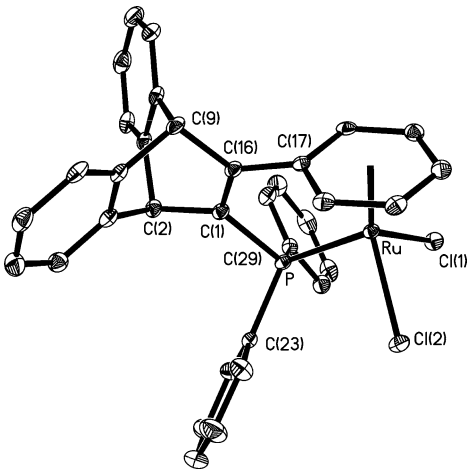
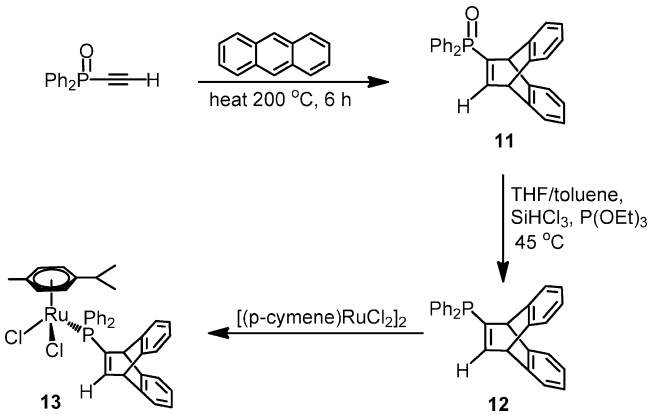


Figure 2. Molecular structure of [Ru(κ(*P*)-η^6-{11-(diphenylphosphino)-12-phenyl-9,10-dihydro-9,10-ethanoanthracene})Cl_2] (**10**). Hydrogen atoms and the chloroform molecule of crystallization have been omitted for clarity. Ellipsoids are at the 40% probability level.

electron donor in a κ(P)-η^6 manner, bonded through the phosphorus atom and tethered by the proximal phenyl ring attached to the two-carbon bridge of the bicyclic framework. This is the first example of a KITPHOS monophosphine coordinating in such a manner and is particularly unusual, since it is the first example of a constrained-geometry complex in which a κ(P)-bonded diphenylphosphino group and an η^6-coordinated arene are linked by an unsaturated two-carbon tether; the overwhelming majority of related complexes typically contain a three-carbon saturated tether. Faller has reported that 2-dicyclohexylphosphino-2′-(*N*,*N*-dimethylamino)biphenyl forms the related tethered ruthenium half-sandwich complex [Ru{η^6:η^1-2-dicyclohexylphosphino-2′-(*N*,*N*-dimethylamino)biphenyl}Cl_2], with the η^6-coordinated dimethylamino-containing aryl ring connected to the κ(*P*)-dicyclohexylphosphino group via the double bond of an arene ring; interestingly, this complex was resolved into its planar chiral enantiomers, which were used as catalyst precursors for a number of asymmetric transformations.[31] The six Ru−C(arene) distances in **10** lie between 2.128(2) and 2.220(2) Å, which are within the range reported for related complexes such as [{η^6-$C_6H_5CH_2CH_2CH_2P(C_6H_5)_2$}$RuCl_2$],[32] [Ru{$\eta^6$:$\eta^1$-*o*-$(C_6H_4)(CH_2OH)(CH_2CH_2PPh_2)$}$Cl_2$],[33] and [Ru{(*R*)-$\eta^1$-$PPh_2(CH_2)_2CH(CH_3)$-$\eta^6$-$C_6H_5$}$Cl_2$].[34] While the η^6-aryl ring is close to planar, with a maximum deviation of −0.0159 (16) Å from the least-squares mean plane, C(16) bends quite markedly toward the metal center and lies 0.267(4) Å below this plane; presumably the result of strain enforced by only having a two-carbon tether linking the η^6-arene to the phosphine. The Ru(1)−P(1) distance of 2.3487(6) Å is similar to that of 2.3527(6) Å in **9** and close to that of 2.3199(6) Å found in [$RuCl_2${(*R*)-η^1-$PPh_2(CH_2)_2CH(CH_3)$-η^6-C_6H_5}].[34] The P(1)−Ru(1)−Cl(1) and P(1)−Ru(1)−Cl(2) angles of 90.60(2) and 91.59(2)°, respectively, and the Cl(1)−Ru(1)−Cl(2) angle of 86.77(2)° lie within a fairly narrow range and are all surprisingly close to the corresponding angles in **9**, suggesting that constraining the coordinated phosphino group and arene ring via a two-carbon unsaturated tether does not have a marked influence on the coordination geometry at the metal. The Ru−C bond that lies trans to the phosphorus atom (Ru(1)−C(20) = 2.254(2) Å) is slightly longer than the remaining five Ru(1)−C bonds (2.128(2)−2.220(2) Å). Similar bond length patterns have previously been reported for related arene ruthenium(II) complexes of tertiary monophosphines[35] and attributed to the bond-lengthening trans effect of the tertiary phosphine ligand.

With the intention of comparing the performance of catalysts generated from ruthenium(II) complexes of κ(P)- and κ(P):η^6-coordinated monophosphines in the direct ortho arylation of 2-phenyl-substituted N-heterocycles (vide infra), it was also necessary to prepare a benchmark or reference precatalyst based on a KITPHOS monophosphine that could not form a constrained-geometry complex. For this, we chose **12**, since it lacks a proximal phenyl ring on the biaryl-like fragment and as such will only coordinate to ruthenium as a κ(P) donor; in this regard **12** can be described as a triaryl-like phosphine. Monophosphine **12** was prepared by following the procedure previously outlined for **8**, based on the Diels−Alder cycloaddition between diphenylethynylphosphine oxide and anthracene. Unfortunately, reduction of the resulting oxide proved to be problematic, as the use of conventional conditions (110 °C, trichlorosilane/NEt_3) gave a multitude of products, of which the desired phosphine was only a minor component. Fortunately, optimum conditions were identified after persistent modification and mild heating (45 °C) of a toluene−THF solution of **11** in the presence of trichlorosilane and triethyl phosphite eventually gave **12** in near-quantitative yield (Scheme 2). The ^{1}H NMR spectrum of **12** contains a

Scheme 2



triplet of doublets at δ 6.81 associated with the vinylic proton, while the bridgehead protons appear as a doublet at δ 5.15 and a doublet of doublets at 5.0; the corresponding signals for the vinylic and bridgehead carbon atoms appear at δ 146.7 and δ 55.2 and 52.5, respectively.

The *p*-cymene ruthenium(II) complex **13** was prepared in near-quantitative yield by treatment of [(*p*-cymene)$RuCl_2$]$_2$ with **12** at room temperature for 4 h. The ^{31}P NMR spectrum contains a resonance at δ 23.1, which is close to that of δ 23.9 reported above for **9**. Crystals suitable for X-ray structure analysis were grown to compare the key structural parameters with those for the corresponding complexes of triphenylphosphine and the triaryl-like (1,2-diphenylvinyl)-diphenylphosphine. A perspective view of the molecular structure is shown in Figure 3. The molecular structure of **13** shows that the Ru−P and Ru−Cl bond lengths and the associated bond angles at ruthenium are very close to those in

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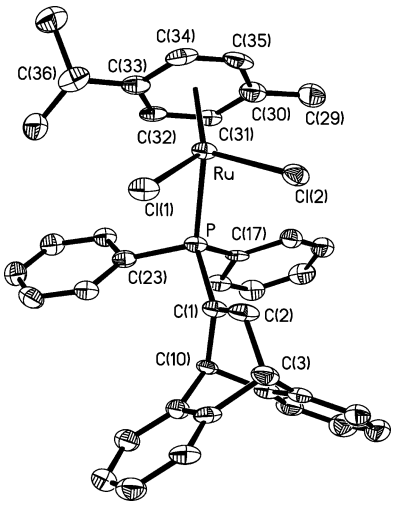
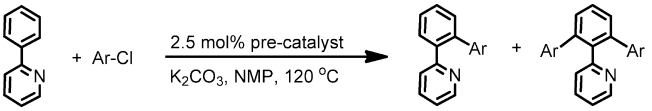


Figure 3. Molecular structure of [(*p*-cymene)Ru(κ(*P*)-{2-(diphenylphosphino)-9,10-dihydro-9,10-ethanoanthracene})Cl_2] (**13**). Hydrogen atoms have been omitted for clarity. Ellipsoids are at the 40% probability level.

[(*p*-cymene)Ru(PPh_3)Cl_2][28] and [(*p*-cymene)Ru{(1,2-diphenylvinyl)diphenylphosphine}Cl_2].[30]

In an extension of our reasoning that the core structural architecture of KITPHOS monophosphines resembles a biaryl monophosphine, **12** is a potential surrogate for triphenylphosphine. As such, the direct arylation of 2-phenyl-substituted N-heterocycles was considered an ideal benchmark transformation with which to undertake a comparative study to investigate whether the biaryl-like fragment influences catalyst performance, particularly since [(*p*-cymene)Ru(PPh_3)Cl_2] has already been shown to form an efficient catalyst for ortho arylations.[36] In addition, since Peris and co-workers have reported that the arene ligand affects catalyst performance,[37] a comparison between the efficiency of catalysts generated from precursors based on KITPHOS monophosphines **8** and **12** was considered worthwhile, since the former coordinates in a κ(P)-η^6 manner while the latter can only coordinate as a κ(P) donor. Our preliminary evaluation focused on the arylation of 2-phenylpyridine with a range of aryl chlorides using 2 mol % of catalyst precursor in 1-methyl-2-pyrrolidone (NMP) with potassium carbonate as base, full details of which are provided in Table 1. Comparative catalyst testing for the arylation of 2-phenylpyridine with chlorobenzene revealed that catalysts generated from **9** and **10** both outperformed that formed from [(*p*-cymene)$RuCl_2$]$_2$, albeit marginally, the former giving conversions of 76 and 74%, respectively, to monophenylated product, while the latter only reached 59% conversion in the same time. Gratifyingly, using previously optimized conditions,[30] good conversions and isolated yields of monoarylated product were obtained across a range of electron-poor as well as electron-rich aryl chlorides; in each case a minor amount of diarylated product was also obtained. Although slightly higher conversions and yields of diarylated product could be obtained by using an excess of aryl chloride and potassium carbonate, the catalyst system remained selective for monoarylation; in this regard, phosphine complexes of ruthenium(II) have previously been reported to favor monoarylation over diarylation.[39] However, the selectivity of direct arylation catalyzed by a combination of $RuCl_3 \cdot xH_2O$ and PPh_3 has recently been shown to be markedly dependent on the base, with K_2CO_3 favoring

Table 1. Ruthenium(II) Catalyzed Ortho Arylation of 2-Phenylpyridine with Aryl Chlorides[a]



entry	aryl chloride	precat.	monoarylation (%)[b,c]	diarylation (%)[b]
1	C_6H_5	[(*p*-cymene)$RuCl_2$]$_2$	59 (52)	6
2	C_6H_5	**9**	76 (72)	9
3	C_6H_5	**10**	74 (69)	9
4	C_6H_5	**13**	70 (62)	8
5	4-$MeOC_6H_4$	**9**	76 (73)	8
6	4-$MeOC_6H_4$	**10**	77 (72)	8
7	4-$MeOC_6H_4$	**13**	70 (66)	9
8	4-MeC_6H_4	**9**	75 (71)	10
9	4-MeC_6H_4	**10**	71 (68)	9
10	4-MeC_6H_4	**13**	74 (67)	9
11	4-MeC(O)C_6H_4	**9**	63 (60)	12
12	4-MeC(O)C_6H_4	**10**	63 (58)	15
13	4-MeC(O)C_6H_4	**13**	60 (55)	16
14	4-CNC_6H_4	**9**	57 (54)	16
15	4-CNC_6H_4	**10**	54 (50)	17
16	4-CNC_6H_4	**13**	52 (48)	13
17	3-$Me_2NC_6H_4$	**9**	67 (64)	4
18	3-$Me_2NC_6H_4$	**10**	61 (54)	6
19	3-$Me_2NC_6H_4$	**13**	66 (58)	6
20	4-$EtO_2CC_6H_4$	**9**	64 (61)	3
21	4-$EtO_2CC_6H_4$	**10**	67 (62)	5
22	4-$EtO_2CC_6H_4$	**13**	62 (55)	5

[a]Reaction conditions: 0.5 mmol of Ar−Cl, 0.5 mmol of 2-phenylpyridine, 0.5 mmol of K_2CO_3, 2.5 mol of **9**, **10**, or **13**, 2 mL of NMP, 120 °C, 24 h. [b]Conversions were determined by analysis of the ^{1}H NMR spectrum of the reaction mixture using bromomesitylene as internal standard. Average of two runs. [c]Isolated yield in parentheses.

monoarylation while Na_2CO_3 was selective for diarylation, under the same conditions.[38] Table 1 also shows that the catalyst generated from **10** gave conversions to the mono- and diarylated products similar to those generated from **9**, for all substrates examined, which could be taken as evidence for the generation of a common active species; this is not entirely surprising, since **9** cleanly and nearly quantitatively converts into **10** upon prolonged heating in chlorobenzene at 120 °C. To complete the comparison, the influence of the constrained-geometry coordination sphere was investigated by comparing the performance of the catalyst generated from **10** with that generated from **13**, since the latter lacks the proximal biaryl-like phenyl ring and thus cannot form a constrained-geometry complex. The conversions obtained with the catalyst generated from **13** matches those achieved with **10**, which may indicate that constraining the phenyl ring and the diphenylphosphino group by a tether does not have a marked affect on catalyst efficiency or that the same active species is generated regardless of the precatalyst. In addition, since the catalyst generated from [(*p*-cymene)$RuCl_2$]$_2$ is consistently less efficient than that generated from **9** and **10**,[39] albeit only marginally, it would be reasonable to suggest that the phosphino group and/or the arene ring may remain coordinated during catalysis. The encouraging performance of catalysts generated from **9** and **10** for the ortho arylation of 2-phenylpyridine prompted us to

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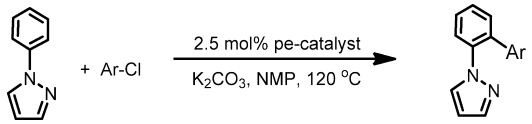
extend our studies to include the arylation of N-phenylpyrazole. As shown in Table 2, good conversions were obtained for a

Table 2. Ruthenium(II) Catalyzed Ortho Arylation of *N*-Phenylpyrazole with Aryl Chlorides[a]



entry	aryl chloride	precat.	monoarylation (%)[b,c]	diarylation (%)[b]
1	C_6H_5	[(*p*-cymene)$RuCl_2$]$_2$	46 (39)	17
2	C_6H_5	**9**	58 (53)	14
3	C_6H_5	**10**	56 (50)	14
4	C_6H_5	**13**	54 (49)	19
5	4-$MeOC_6H_4$	**9**	68 (62)	10
6	4-$MeOC_6H_4$	**10**	69 (66)	10
7	4-$MeOC_6H_4$	**13**	61 (57)	17
8	4-MeC_6H_4	**9**	58 (26)	16
9	4-MeC_6H_4	**10**	62 (55)	15
10	4-MeC_6H_4	**13**	56 (53)	20
11	4-$MeC(O)C_6H_4$	**9**	54 (49)	16
12	4-$MeC(O)C_6H_4$	**10**	60 (57)	12
13	4-$MeC(O)C_6H_4$	**13**	44 (40)	23
14	4-CNC_6H_4	**9**	52 (49)	8
15	4-CNC_6H_4	**10**	54 (51)	7
16	4-CNC_6H_4	**13**	44 (43)	20
17	3-$Me_2NC_6H_4$	**9**	52 (49)	14
18	3-$Me_2NC_6H_4$	**10**	55 (52)	12
19	3-$Me_2NC_6H_4$	**13**	51 (47)	19
20	4-$EtO_2CC_6H_4$	**9**	57 (54)	11
21	4-$EtO_2CC_6H_4$	**10**	59 (56)	8
22	4-$EtO_2CC_6H_4$	**13**	51 (49)	18

[a]Reaction conditions: 0.5 mmol of Ar−Cl, 0.5 mmol of *N*-phenylpyrazole, 0.5 mmol of K_2CO_3, 2.5 mol of **9**, **10**, or **13**, 2 mL of NMP, 120 °C, 36 h. [b]Conversions were determined by analysis of the ^{1}H NMR spectrum of the reaction mixture using bromomesitylene as internal standard. Average of three runs. [c]Isolated yield in parentheses.

selection of aryl chlorides, although slightly longer reaction times were required to reach similar levels of conversion in comparison to the corresponding reaction with 2-phenylpyridine. As described above, the catalysts generated from **9** and **10** are slightly more efficient than [(*p*-cymene)$RuCl_2$]$_2$, with the former reaching conversions of 59 and 57% for the monoarylated product, respectively, compared with 46% for the latter. In contrast to the arylation of 2-phenylpyridine, the catalyst derived from **13** was slightly less selective than the corresponding systems generated from **9** and **10**, giving good conversions but more diarylated product in the same time.

In conclusion, the KITPHOS monophosphine **8** has been shown to coordinate as a conventional κ(P) donor in [(*p*-cymene)Ru{PPh_2-(Ph)-KITPHOS}Cl_2] (**9**) and in a κ(P)-η^6 manner as an eight-electron donor in [Ru{$\kappa(P)$-η^6-PPh_2-(Ph)-KITPHOS}Cl_2] (**10**); the latter is the first example of a constrained-geometry complex in which a κ(P)-bonded diphenylphosphino group and an η^6-coordinated proximal phenyl ring are connected by an unsaturated two-carbon tether. Comparative studies revealed that both **9** and **10** formed highly efficient catalysts for the direct arylation of 2-phenylpyridine and *N*-phenylpyrazole with a range of aryl chlorides, giving comparable conversions and selectivities, while the catalyst derived from **13** gave good conversions for both substrates but slightly lower selectivities for *N*-phenylpyrazole across a range of electrophiles. Even though the κ(P)- and κ(P)-η^6 coordination of KITPHOS monophosphines was not manifested in catalyst performance for direct ortho arylation, we are particularly excited and encouraged about the broader applications of biaryl-like KITPHOS monophosphines in ruthenium-based catalysis, since the introduction of a substituent at the 2- or 5-position of the proximal biaryl-like phenyl ring will render the corresponding constrained-geometry complex chiral, which when resolved could be used for Lewis acid catalyzed asymmetric C−C bond forming reactions such as Diels−Alder and hetero Diels−Alder cycloadditions or the Mukaiyama reaction. In this regard, since KITPHOS monophosphines are constructed from a 1-alkynylphosphine oxide and anthracene, it will be relatively straightforward to vary the substitution pattern of the proximal aryl ring in order to control the stereochemical environment within the coordination sphere of the metal in order to achieve efficient catalysis.

EXPERIMENTAL SECTION

General Procedure for the Ruthenium-Catalyzed Ortho Arylation of 2-Phenyl-Substituted N-Heterocycles with Aryl Chlorides. A flame-dried Schlenk flask charged with 2-phenylpyridine (0.071 mL, 0.5 mmol), aryl chloride (0.5 mmol), catalyst (2.5 mol %, 0.0125 mmol), potassium carbonate (0.138 g, 0.5 mmol), and 1-methyl-2-pyrrolidinone (2 mL) was stirred and heated at 120 °C for the allocated time. After the reaction mixture had cooled to room temperature, bromomesitylene (0.076 mL, 0.5 mmol) was added as internal standard and the resulting mixture quenched with water and extracted with diethyl ether (3 × 10 mL). The organic layers were combined, washed with brine, dried over magnesium sulfate, concentrated under reduced pressure, and analyzed by ^{1}H NMR spectroscopy to determine the conversion before being purified by column chromatography, with hexane/ethyl acetate (5/1 v/v) as eluent. Known products were characterized by NMR spectroscopy and mass spectrometry and unknown products by NMR spectroscopy, high-resolution mass spectrometry, and elemental analysis.

ASSOCIATED CONTENT

Supporting Information

Text giving full details of experimental procedures, characterization data for all new compounds, and details of catalyst testing and,CIF files giving details of crystal data, structure solution, and refinement, atomic coordinates, bond distances, bond angles, and anisotropic displacement parameters for compounds **9**, **10**, and **13**. This material is available free of charge via the Internet at http://pubs.acs.org.

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