Phospha-adamantanes as Ligands for Palladium-Catalyzed Cross-Coupling Reactions

By

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ABSTRACT

New and robust methodologies have been designed for palladium-catalyzed cross-coupling reactions involving a novel class of tertiary phosphine ligand incorporating a phospha-adamantane framework. It has been realized that bulky, electron-rich phosphines, when used as ligands for palladium, allow for cross-coupling reactions involving even the less reactive aryl halide substrates with a variety of coupling partners. In an effort to design new ligands suitable for carrying out cross-coupling transformations, the secondary phosphine, 1,3,5,7-tetramethyl-2,4,8-trioxa-6-phosphaadamantane was converted into a number of tertiary phosphine derivatives. The ability of these tertiary phosphaadamantanes to act as effective ligands in the palladium-catalyzed Suzuki cross-coupling was examined. 1,3,5,7-Tetramethyl-6-phenyl-2,4,8-trioxa-6-phosphaadamantane (**PA-Ph**) used in combination with $Pd_2(dba)_3$ permitted the reaction of an array of aryl iodides, bromides and chlorides with a variety arylboronic acids to give biaryls in good to excellent yields. Subsequently, palladium complexes of **PA-Ph** were prepared and isolated in high yields as air stable palladium bisphosphine complexes. Two different kinds of crystals were isolated and upon characterization revealed two complexes, $Pd(PA\text{-}Ph)_2$.dba and $Pd(PA\text{-}Ph)_2O_2$. Preliminary screening for their catalytic activity indicated that the former is more reactive than the latter. $Pd(PA\text{-}Ph)_2$.dba was applied as the catalyst for Sonogashira cross-coupling reactions of aryl iodides and bromides and in the reactions of aryl bromides and chlorides with ketones to give α-arylated ketones at mild temperatures in high yields.

ACKNOWLEDGEMENTS

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Lovingly dedicated to my wife,

Heartwill.

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EXPERIMENTAL

INTRODUCTON

1.0 Palladium-catalyzed reactions

Although the majority of the fundamental processes that are catalyzed by palladium were well established during the mid 1980s, their acceptance and use by organic chemists was minimal until the mid 1990s. As examples of palladium catalysis in the synthesis of highly functionalized, complex molecules accumulated, its acceptance grew, until today, when it has become one of the most commonly used metals in organic synthesis.[1,2] There are several features that make reactions involving Pd particularly useful and versatile. Many of the carbon-carbon bonds forming processes involving Pd reagents are tolerant of a variety of functional groups (such as carbonyl and hydroxyl groups). In addition, Pd reagents and catalysts are generally not sensitive to oxygen (although precautions to avoid oxidation of the phosphine ligands[3] are recommended), moisture, or even to acid (contrast this with many of the Ni(0) complexes that are often extremely sensitive to oxygen).

Palladium exists predominantly in two stable oxidation states, the +2 state and the zero-valent state, and it is the facile redox interchange between these two oxidation states which is responsible for the rich chemistry that palladium complexes display. Each oxidation state has its own unique chemistry. Palladium(II) complexes are used either as stoichiometric reagents or as catalysts while palladium(0) complexes are used as catalysts. Palladium (II) complexes are electrophilic, and tend to react with electron-rich organic compounds, particularly alkenes and arenes. Palladium(II) complexes such as $PdCl_2$ and $Pd(OAc)_2$ are widely used as unique oxidants or as precursors of Pd(0) complexes.[3,4] Palladium(0) complexes are strong nucleophiles and strong bases, and are

usually used to catalyze reactions involving organic halides, acetates and triflates. By far the most commonly used palladium(0) complexes are tetrakis(triphenylphosphine) palladium(0),$Pd(PPh_3)_4$, a yellow, slightly air-sensitive solid,[5] $Pd_2(dba)_3$-$CHCl_3$ (dba = dibenzylideneacetone), air stable purple needles[6]

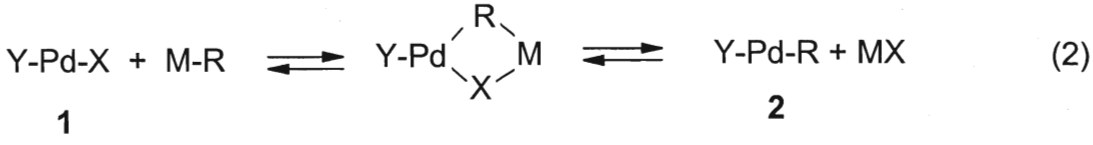
2.0 Mechanistic considerations of palladium(0) catalyzed reactions

Mechanistically, palladium(0) reactions begin with "oxidative" addition of a molecule X-Y to the palladium with cleavage of its covalent bond, forming two new bonds to palladium to give **1** (equation 1).[7,8] Since the two previously nonbonding electrons of Pd are involved in bonding to X and Y, the Pd increases its formal oxidation state by two; i.e. Pd(0) is oxidized to Pd(II).

$$Pd(0) + X\text{-}Y \xrightarrow{\text{Oxidative addition}} \underset{\mathbf{1}}{X\text{-}Pd(II)\text{-}Y} \qquad (1)$$

A number of different covalent bonds are capable of undergoing this oxidative addition to Pd(0). The most common are C-X (X = halogen and pseudo-halogen), C-O, H-H, C-H, Si-H, M-H, M-M (M = main group metals), and H-X bonds. Also N-H, X-X, O-H, and even C-C bonds undergo oxidative addition. Most frequently observed is the oxidative addition of organic halides of sp^2 carbons and the rate of the addition decreases in the following order: C-I > C-Br > C-OTf >> C-Cl >>> C-F. Others systems that undergo oxidative addition include: acyl halides (RCO-X), aldehydes (RCO-H), allylic compounds ($RCH{=}CHCH_2$-X, X = halogen, esters, NO_2, SO_2R, etc.), sulfonyl halides (RSO_2-X), and H-H.[3,9]

Organometallic compounds M-R and hydrides M-H of main group metals such as Mg, Zn, B, Al, Sn, Si, and Hg can then react with X-Pd-Y complexes with the organic group or hydride transferred to Pd by an exchange reaction of X with R or H. In other words, the alkylation of Pd takes place to give **2** (Equation 2). A driving force of the reaction, which is called transmetallation, is ascribed to the difference in the electronegativities of two metals. A typical example is the phenylation of phenylpalladium iodide with phenyltributyltin to form diphenylpalladium **3** (equation 3).



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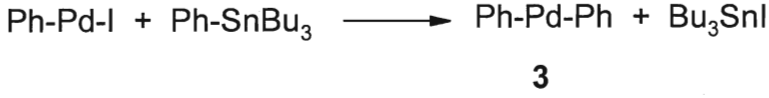


(3)

The final step of the catalytic cycle is reductive elimination step: a unimolecular decomposition pathway, which involves the loss of two one-electron ligands from the palladium centre, combining them to form a single elimination product (equation 4). By the reductive elimination, both the coordination number and the formal oxidation state of palladium(II) are reduced by two to generate Pd(0), as shown in (equation 5). Pd(0) species, thus generated, can undergo another round of oxidative addition and continue the catalytic cycle (Figure 1).[2,3]

$$\text{Y-Pd-R} \longrightarrow \text{R-Y} + \text{Pd(0)} \qquad (4)$$

$$\text{Ph-Pd-Ph} \longrightarrow \text{Ph-Ph} + \text{Pd(0)} \qquad (5)$$

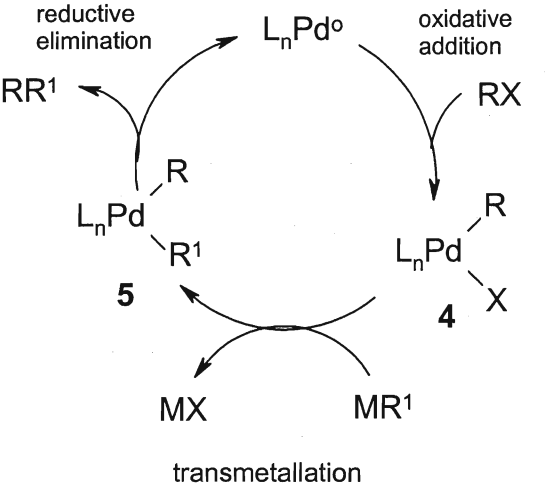


Figure **1**. Generalised mechanism for palladium-catalyzed cross-coupling reactions.

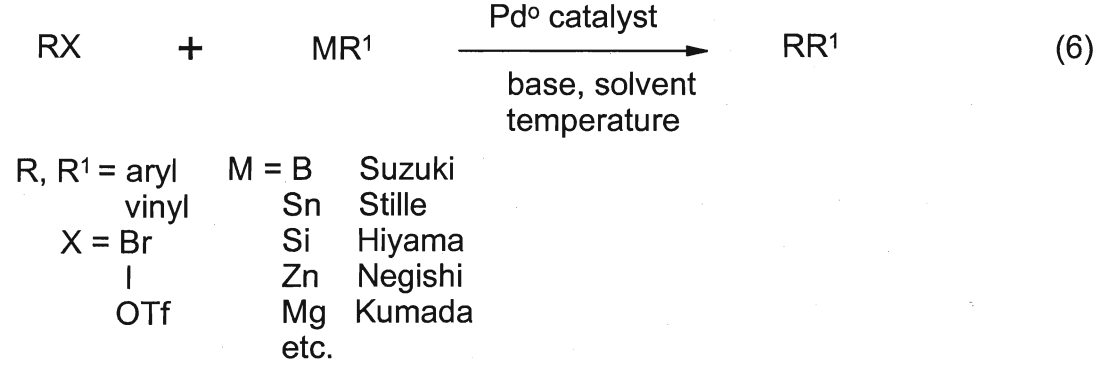
While the general cycle described can be augmented to include other processes including ligand exchanges or beta-hydride eliminations, excellent evidence exists for the key intermediates (**4** and **5**) which have been characterised by isolation or spectroscopic analyses.[8,10] Furthermore, it should also be noted that the great majority of cross-coupling reactions catalyzed by Ni(0) and Fe(I) are also rationalised in terms of this common catalytic cycle.[9]

3.0 Specific palladium-catalyzed carbon-carbon bond forming reactions.

The palladium-catalyzed cross-coupling reaction of aryl and vinyl halides/triflates with organometallic reagents serves as one of the most versatile and powerful methods for formation of carbon-carbon bonds (equation 6) as well as carbon-heteroatom bonds.[11]

Depending on the nature of the organometallic reaction partner, each variation is generally named after its discoverer (equation 6). For example, reactions employing organoboranes are termed Suzuki reactions while organotin reagents are used in the Stille reaction. It should be noted that the R^1 group of the organometallic reagent could be any of a variety of saturated or unsaturated groups, for example, alkyl, aryl, vinyl, and alkynyl.[9,11]

Most magnesium, tin, and zinc reagents are sufficiently reactive to undergo transmetallation with palladium without the need for an additive (base); boron and silicon reagents, on the other hand, are usually reluctant to transmetallate in the absence of an activator. As a consequence, Suzuki and Hiyama cross-couplings are typically carried out in the presence of a base, the role of which is to form a higher valent, more reactive complex.[11]



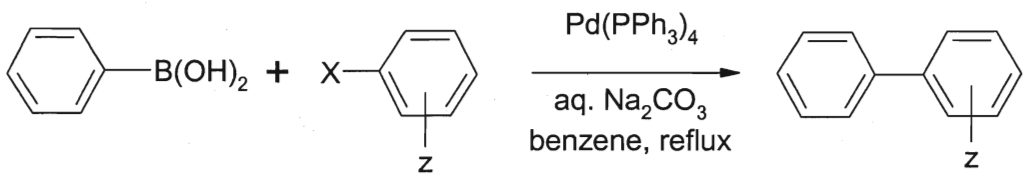
Until recently, nearly all reports of palladium-catalyzed couplings described the use of organic bromides, iodides, and triflates as substrates.[9] Organic chlorides were noticeably uncommon partners, despite the fact that, among the halides, chlorides are arguably the most useful single class of substrates, because of their lower cost and availability.[12] Unfortunately, chlorides were generally unreactive under the conditions

employed to couple bromides, iodides, and triflates.[13] The low reactivity of chlorides is usually attributed to the strength of the C-Cl bond (bond dissociation energies for Ph-X: Cl: 96 kcal mol^{-1}; Br: 81 kcal mol^{-1}; I: 65 kcal mol^{-1}),[12] which leads to reluctance by aryl chlorides to oxidatively add to Pd(0) centre, the critical initial step in palladium-catalyzed coupling reactions (figure 1).[14]

Specific examples of palladium-catalyzed cross-coupling reactions are presented below.

3.1 Suzuki Cross-Coupling Reactions

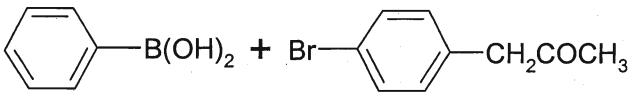
The Suzuki-Miyaura reaction, where organoboron reagents are employed as the coupling partner with aryl halides (or pseudo halides), is one of the most successful strategies for carbon-carbon bond formation.[9,15-17] Organoboron compounds possess

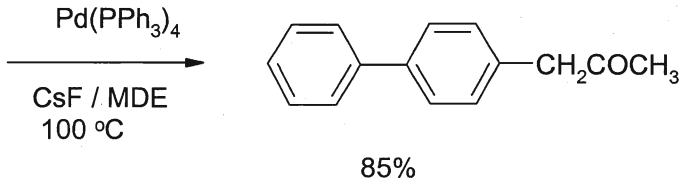


(7)

many attractive features. They are commercially available, air- and moisture-stable reagents that can be handled without special precautions. Additionally, the boron-containing by-product of the Suzuki cross-coupling can readily be separated from the desired product.[15] The standard conditions first reported by Suzuki for the preparation of biaryls are shown in equation 7[18] and generally involve a combination of $Pd(PPh_3)_4$ or $PdCl_2(PPh_3)_2$ and aqueous Na_2CO_3.[19,20]

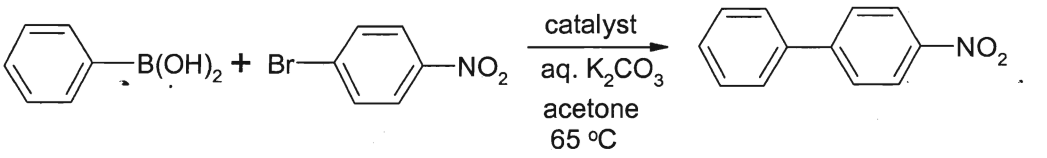
Various modifications have been made to the reaction conditions since the initial studies. For example, other bases such as Et_3N,[21] $NaHCO_3$,[19] Cs_2CO_3[22], Tl_2CO_3,[23] and K_3PO_4,[24] with or without Bu_4NCl[25] and 18-crown-6[22] also have been employed. In addition, extremely mild conditions using CsF or Bu_4NF (Equation 8) have also allowed for the synthesis of various functionalised biaryls.[26]





(8)

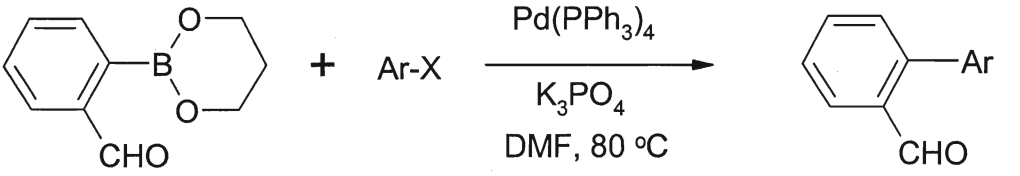
Generally, phosphine-based palladium catalysts are used in cross-coupling reactions since they are stable on prolonged heating; however, there are successful Suzuki cross-coupling reactions using palladium catalysts without a phosphine ligand such as $Pd(OAc)_2$, $[\eta^3\text{-}C_3H_5)PdCl]_2$, and $Pd_2(dba)_3.C_6H_6$ have also been achieved.[27,28] Phosphine-free palladium reactions are approximately 1 order of magnitude more reactive than $ArPd^{III}(PPh_3)_2$, both of which are in turn markedly more reactive than $Pd(PPh_3)_4$ (equation 9).[9]



(9)

catalyst:
$Pd(PPh_3)_4$ (8h, 23%); $PhPd(PPh_3)_2$ (0.33 h, 53%); $Pd(OAc)_2$ (0.75h, 98%)

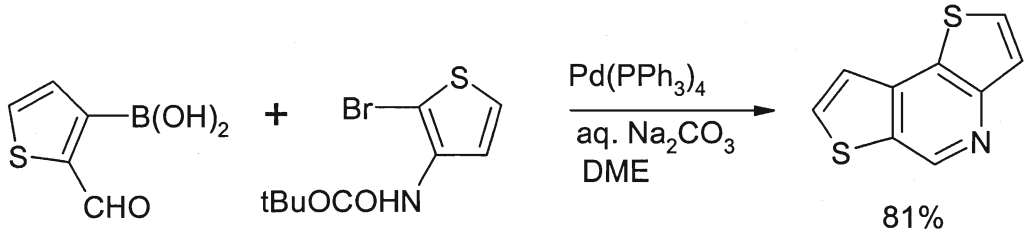
While the Suzuki reaction proceeds more rapidly under homogeneous conditions (aqueous base in DME), reasonable yields are also obtained under heterogeneous conditions,[11] for example, K_2CO_3 suspended in toluene.[29] Suzuki reactions can also carried out in aqueous medium by using water-soluble phosphine ligands such as *m*-$NaO_3SC_6H_4PPh_2$.[30] However, reactions under aqueous conditions often give undesirable results due to competitive hydrolytic deboronation.[31] The rate for the cleavage of $XC_6H_4B(OH)_2$ with water at Ph 6.7 is shown as follows: (relative to phenylboronic acid) 2,6-dimethoxy (125), 2-F (77), 2-Cl (59) 2-MeO (11), 4-MeO (4.2), 2-Me (2.5), 3-F (2.3), 3-Me (2), 4-F (1.7).[32] For instance, the coupling of 2-formylboronic acid with 2-iodotoluene at 80 °C using an aqueous Na_2CO_3 in DME gives only 54% of biaryl with benzaldehyde (39%). The yields can be improved to 89% by using the corresponding ester of boronic acid and anhydrous K_3PO_4 suspended in DMF (equation 10).[33]



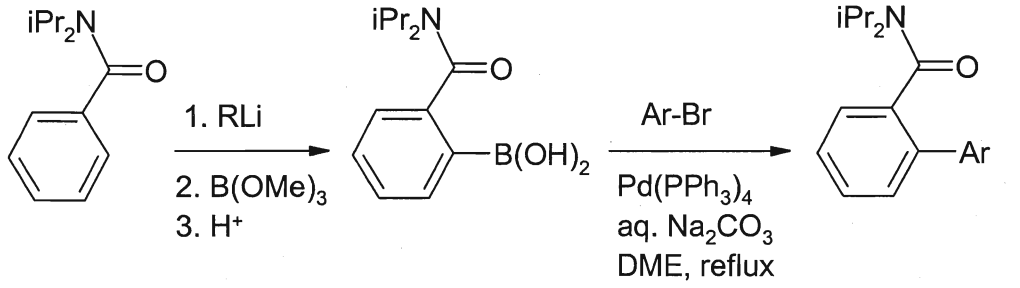
(10)

Ar-X: iodomesitylene (73%), $2\text{-}MOMOC_6H_4I$ (85%), $2\text{-}MeO_2CC_6H_4Br$ (63%)

While substrates containing sterically less demanding *para*- and *meta*-substituents are routinely used, substrates bearing *ortho*-functional groups or heteroaromatic rings can also be used to good effect in the Suzuki reaction. Gronowitz has shown that unsymmetrical substituted bithienyls[19,34] and thienylpyridines[35] can be regioselectively synthesized by the cross-coupling reaction of thienylboronic



(11)

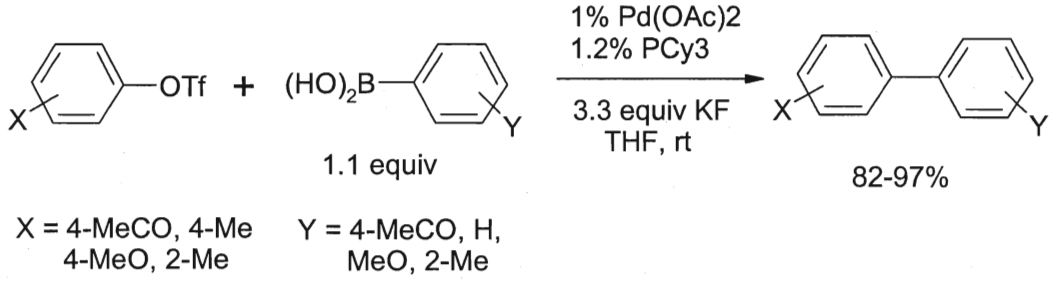


(12)

acids (equation 11). The ready availability of *ortho*-functionalised arylboronic acids by directed *ortho*-metallation-boronation sequence provides a synthetic link to the cross-coupling protocol. Snieckus has demonstrated that the sequence has considerable scope for the synthesis of unsymmetrical biaryls, heterobiaryls, and terphenyls[36] (equation 12).

While the cross-coupling reaction with organic halides has been studied predominantly, it has been most recently discovered that trifluoromethanesulfonates (triflates) undergo a clean coupling with organoboron compounds.[37] The triflates are valuable partners for the cross-coupling reaction,[38] due in part to their easy access from

phenols or carbonyl enolates which allow the selective formation of aryl and 1-alkenyl electrophiles. Since aryl triflates are less reactive than their corresponding iodides and bromides,[39] elevated reaction temperatures have been employed in essentially all of the reactions of aryl triflates. However, in 2000, Fu and coworkers reported that using $Pd(OAc)_2/PCy_3$ (Cy = cyclohexyl) catalyst system they can efficiently cross-couple a broad spectrum of aryl triflates and arylboronic acids at room temperature in excellent yields.[40] (equation 13). They also noted that variation in the electronic nature of the aryl triflate and of the arylboronic acid is well tolerated, as is the presence of *ortho*-substituents.



(13)

The Suzuki reaction has been used extensively in the synthesis of natural and unnatural products and pharmaceuticals such as saddle-shaped host compounds,[41a] ferrocene derivatives,[41b] bis-cyclometalating N-C-N hexadentated ligands,[41c] helically chiral ligands,[41d] michellamine,[28] biphenomycine A,[41e] vancomycin,[41f] receptor molecules for oxo acids,[41g] leukotriene B4 receptor antagonist,[41h] hemispherand,[41i] 1-1'-bi-2-naphthols,[41j] fascaplysin and streptonigrin alkaloids,[41k] ungerimine and hippadine alkaloids,[41l] and other biaryls.[41] Some examples are summarized in Figure 2. Suzuki reaction has also found application in the synthesis of new materials. Aromatic, rigid-rod polymers play an important role in a number of diverse technologies including high-

performance engineering materials, conducting polymers, and nonlinear optical materials. The cross-coupling reaction of aryldiboronic acids and dihaloarenes for the synthesis of

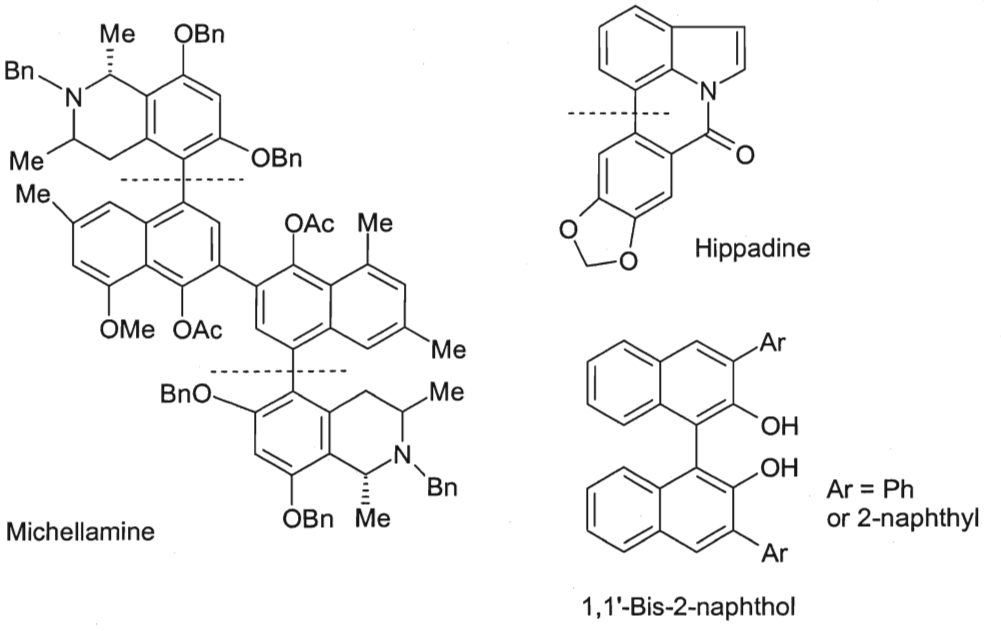


Figure **2**. Synthesis of biaryls.

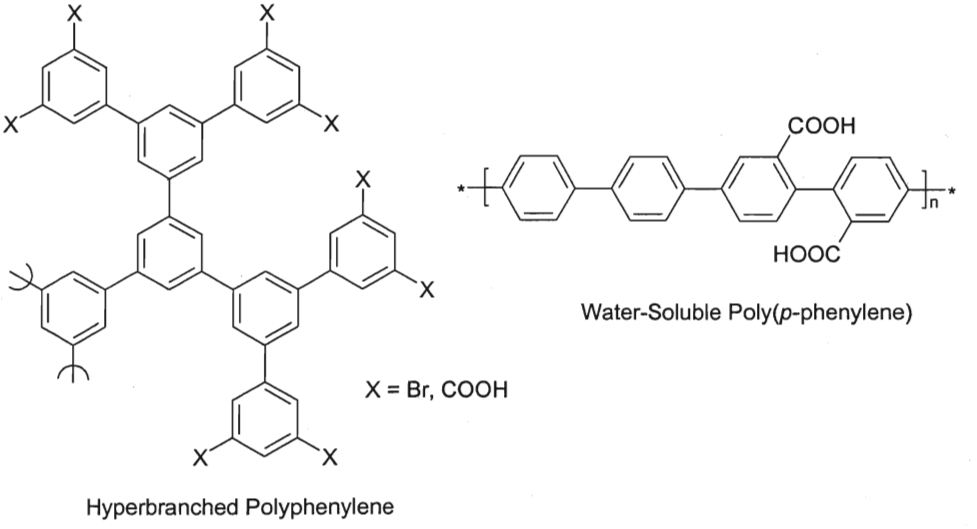


Figure **3**. Aromatic rigid-rod polymers.

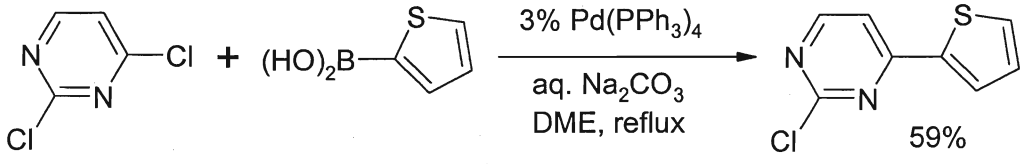
poly(*p*-phenylenes) was first reported by Schluter.[42] The method has been extensively applied to monodisperse aromatic dendrimers, water-soluble poly(*p*-phenylene), planar

poyl(*p*-phenylenes) fixed with the ketoimine bonds, poyl(phenylenes) fused with polycyclic aromatics, and nonlinear optical materials[9] (Figure 3).

3.2 Suzuki reactions of activated and unactivated aryl chlorides

Certain aryl chlorides, specifically, electron-poor aryl chlorides, which are activated toward oxidative addition, have long been known to serve as suitable substrates for Suzuki cross-coupling reactions.[9,11] Thus, Suzuki cross-coupling of pi-deficient heteroaryl chlorides such as chloropyridines can often be achieved with traditional triarylphosphine-based palladium catalysts.[43] This reactivity is important because of the abundance of chlorine-containing nitrogen heterocycles (as compared with bromine- or iodo-containing nitrogen heterocycles) that are commercially available.[9,11,15,16]

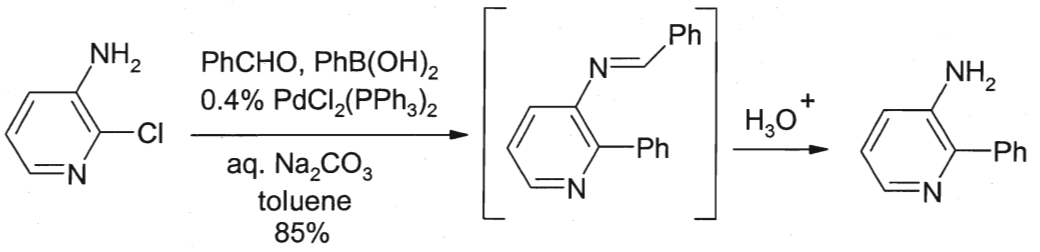
One of the earliest examples of a Suzuki reaction of a heteroaryl chloride was provided by Gronowitz *et al.*, who examined the coupling of 2,4-dichloropyrimidine with 2-thienylboronic acid and established that the 4-chloro group is more reactive than the 2-chloro group (equation 14).[44] Subsequently, other chloro-substituted nitrogen



(14)

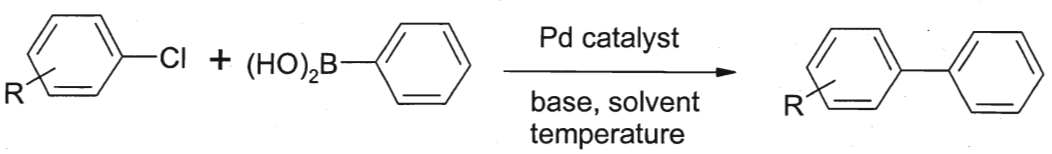
heterocycles have been shown to undergo Suzuki coupling in the presence of traditional catalysts including pyridines, pyridine N-oxides, pyrazines, pyridazines, triazines, quinolines, purines, and other examples.[11]

The methodology has been utilized effectively as part of numerous total syntheses.[44] For example, the use of a Suzuki reaction of a heteroaryl chloride to produce 2-phenyl-3-aminopyridine, a key intermediate in the synthesis of 2-phenyl-3-aminopiperidine (an important pharmacophore present in potent non-peptide NK1



(15)

receptor antagonists) has been reported. Direct coupling of 2-phenyl-3-aminopyridine with phenylboronic acid was unsuccessful; however, a one-pot protection/Suzuki coupling/deprotection sequence furnished the target compound in excellent yield on a greater than 100-gram scale (equation 15).[45]

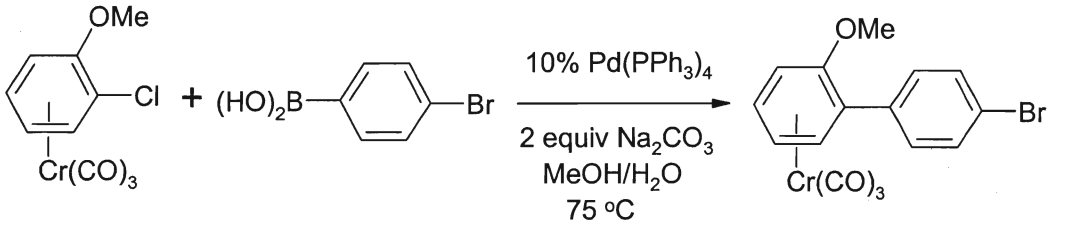


(16)

R = CN, NO_2, COMe, CF_3, CHO, CO_2Me

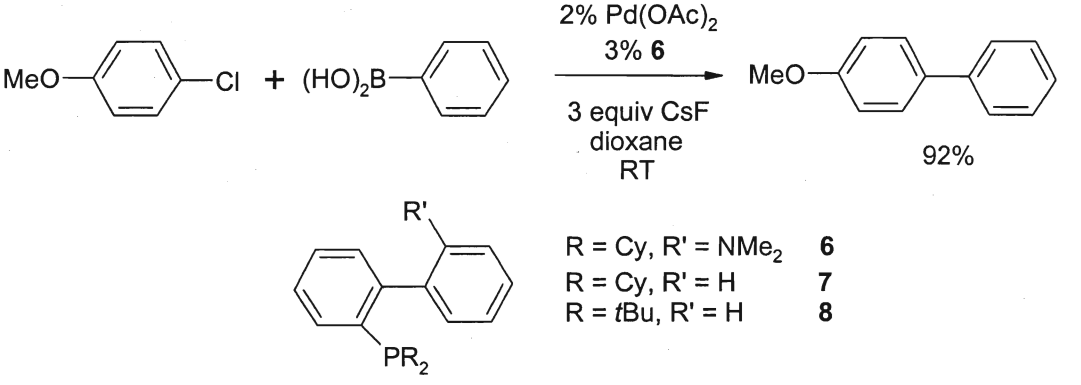
Within the last decade, a number of Suzuki reactions of non-heteroaryl chlorides have been described, and some representative couplings are depicted in equation 16.[39] Equation 17 is a particularly interesting illustration of the activation that can be provided by a powerful electron-withdrawing group (EWG). Electron-withdrawing groups are said

to activate the aryl halide bond towards oxidative addition. Thus, Uemura and co-workers have shown that aryl chlorides that are η^6–bound to $Cr(CO)_3$ are remarkedly reactive coupling partners in Suzuki reactions.[46] The aryl chloride couples with an aryl boronic acid even in the presence of the electron-donating, deactivating ortho-methoxy substituent. Furthermore, no homocoupled 4-bromophenylboronic acid is observed, thus establishing that highly selective activation of a C-Cl bond occurs in the presence of a typically more reactive C-Br bond



(17)

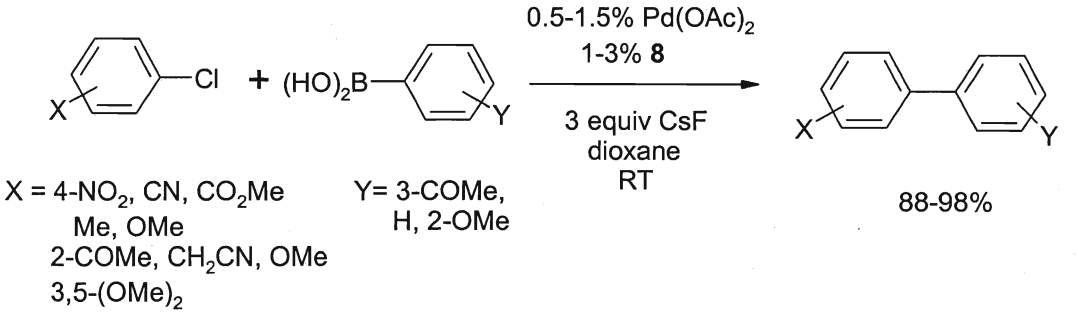
Prior to 1998, there were no reports of effective palladium-catalyzed Suzuki cross-coupling reactions of electron-neutral or electron-rich aryl chlorides. This final hurdle limited the scope of the Suzuki reaction. In 1998, the groups of Buchwald and Fu independently developed catalyst systems that couple a wide range of aryl chlorides in good yields.[39] Buchwald and co-workers reported that amino-phosphane **6** is a very effective ligand for palladium-catalyzed Suzuki reactions of aryl chlorides (equation 18).[47]



(18)

Remarkably, this catalyst system couples a broad spectrum of aryl chlorides, such as electron-neutral and electron-rich substrates, at room temperature. CsF was found to be the base of choice, although the less expensive K_3PO_4 could be used at 100 °C.

Buchwald and co-workers subsequently determined that biphenyl ligands **7** and **8** can be even more effective than **6** in palladium-catalyzed Suzuki reactions of aryl chlorides, thereby establishing that the amino group of aminophosphane is not

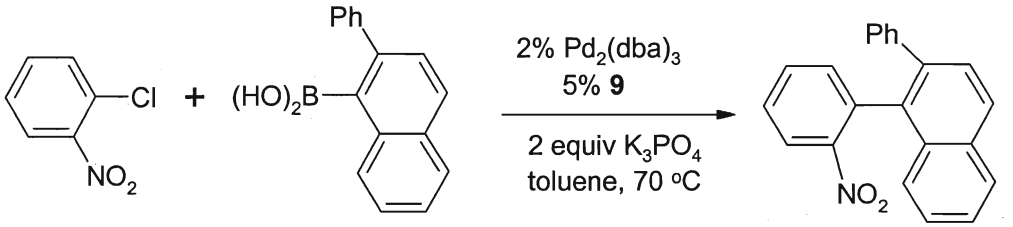


(19)

essential for high activity.[48] Room temperature Suzuki couplings of a wide array of partners can be achieved using ligand **8** with 0.5 – 1.5% Pd and KF as the activator (equation 19).

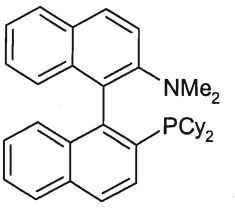
Parrish and Buchwald have developed a polymer-bound dicyclohexylphosphanylbiphenyl ligand that can be employed for Suzuki reactions of electron-neutral and hindered aryl chlorides; the coupling product can be isolated without the need for column chromatography.[49] In addition, binaphthyl derivative **9**, an enantiopure variant of biphenyl ligand **6**, can be applied to the asymmetric synthesis of axially chiral biaryls, which are present in a number of natural products (equation 20).[50] A stabilizing interaction between the *ortho*-aryl group and the palladium *d*-orbital has

been suggested as being responsible for the high activity exhibited by catalysts based on biphenyl ligands.[11]



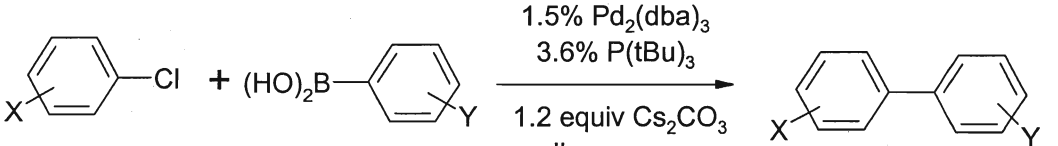
(20)

72% ee
83% yield



9

In the same year as the original report by Buchwald and co-workers, Littke and Fu also described a versatile method for palladium-catalyzed Suzuki cross-coupling of aryl chlorides in which they use a sterically demanding and electron-rich trialkylphosphine, $P(tBu)_3$ (equation 21).[51] A $P(t\text{-}Bu)_3$: Pd ratio between 1.0-1.5:1 was most effective. Deactivated and hindered aryl chlorides were suitable substrates for this catalyst system. In their initial study, $Pd_2(dba)_3$, Cs_2CO_3, and dioxane were employed as the palladium source, activator, and solvent, respectively.



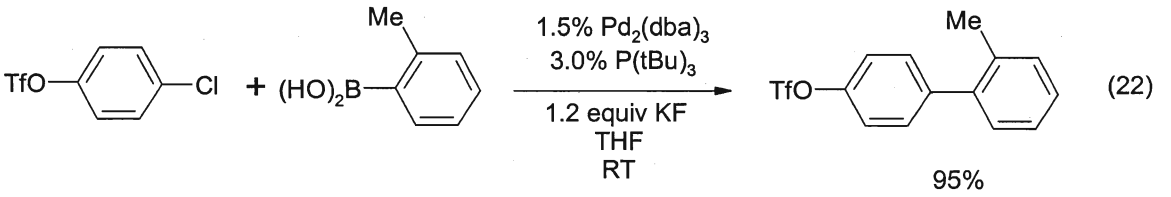
X = 4-COMe, Me
OMe, NH_2
2-Me

Y= 4-CF_3,H,
OMe
2-Me

82-92%

(21)

Fu and co-workers later determined that KF is a more effective additive than Cs_2CO_3, which allowed Suzuki cross-couplings of activated aryl chlorides, including heteroaryl chlorides, to proceed at room temperature.[40] The authors reported that this $Pd/P(tBu)_3$-based catalyst system exhibits a highly unusual reactivity profile and unprecedented selectivity for the coupling of an aryl chloride in preference to an aryl triflate (equation 22).



(22)

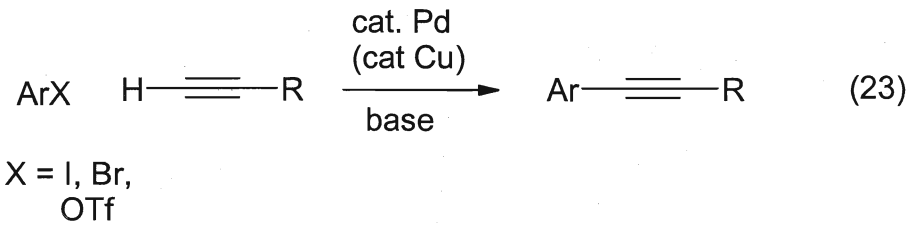
In line with these new developments on the use of bulky phosphine ligands in palladium-catalyzed reactions of aryl chlorides, a number of research groups have described other ligands that can provide active catalysts for palladium-catalyzed Suzuki coupling of aryl chlorides. Guram and co-workers have established that dialkylphosphines are effective ligands for palladium-catalyzed Suzuki reaction of aryl chlorides.[52] In addition, Beller and co-workers have reported that the new bulky ligand di(1-adamantyl)-n-butylphosphane can afford excellent turnover numbers in palladium catalyzed Suzuki reactions.[53]

Until recently, though, trialkylphosphanes were not found to be effective for reactions of unactivated aryl chlorides. However, in 2001, Pickett and Richards indicated that Pd/tris(2-methylferrocenyl)phosphine can afford Suzuki cross-coupling of aryl chlorides in modest yield under milder conditions.[54] Thereafter, Fu and co-workers

reported that a diphenylferrocenylphosphine ligand was also effective for palladium-catalyzed Suzuki cross-coupling reactions of aryl chlorides.[55] Since PPh_3 is ineffective under these conditions, the unusual reactivity of these ligands is attributed to the elcectron donating ability of the ferrocenyl group, relative to a phenyl substituent.

3.3 Sonogahsira reactions

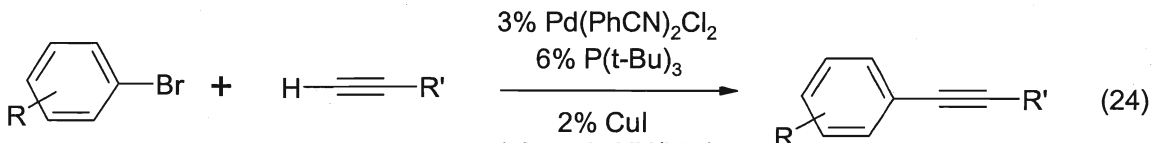
The palladium-catalyzed coupling of terminal alkynes with aryl/vinyl halides and triflates, usually in the presence of copper co-catalyst, is commonly referred to as the Sonogashira reaction (equation 23).[56]



(23)

The Sonogashira reaction constitutes an effective and versatile method of generating non-terminal alkynes from terminal alkynes. It has found wide spread application in industrial synthesis, partly because of its functional group compatibility and the nontoxicity and easy removal of the by-product.[57,58] The order of reactivity with respect to the organic halide has been observed as: vinyl iodide ~ vinyl bromide > aryl iodide > vinyl chloride >> aryl bromide. [58] Aryl chlorides as a whole are generally unreactive marking a major weakness for the Sonogashira reaction. However, there are reports of couplings of activated aryl chlorides, particularly nitrogen-containing heteroaryl chlorides, which afford alkynylated N-heteroaromatic compounds. [59,60]

Although, there are numerous reports dealing with the palladium-catalyzed Sonogashira reaction of aryl/vinyl halides (especially iodides and bromides) in the presence of copper co-catalyst, attention is now turning towards copper-free palladium-catalyzed Sonogashira reactions. [59,61] It is obvious that copper-free palladium-catalyzed reactions have advantage over the traditional Sonogashira reaction, which employs palladium/copper catalyst. Copper-free reactions are much cleaner and easy to purify than reactions contaminated with copper.[62]



(24)

R = 4-COMe, H, Me, OMe, NMe_2
R' = Ph, n-Hex, CMe2(OH), TMS

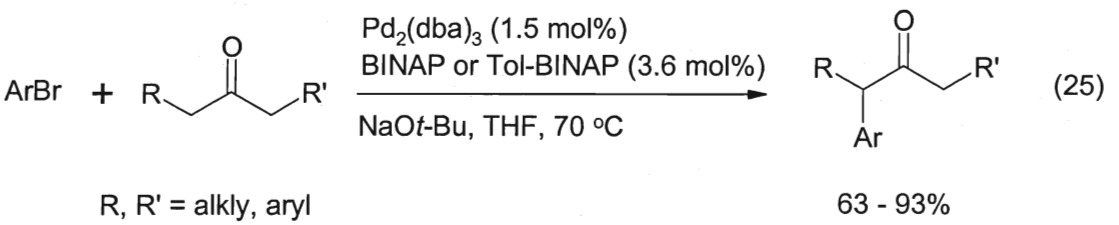
63-95%

In spite of the fact that reactions involving vinyl halides and aryl iodides have been well known to proceed at room temperature, the aryl bromides, until recently, were not reactive at room temperature. The groups of Buchwald and Fu reported in 2000, Sonogashira reaction of aryl bromides at room temperature employing $Pd(PhCN)_2Cl_2$/P(*t*-Bu)$_3$ and CuI catalyst system (equation 24). [63] In the same year, Herrmann and Böhm reported copper-free Sonogashira reaction of aryl bromides at room temperature, in which $Pd_2(dba)_3$/P(*t*-Bu)$_3$ catalyst system was used. [62]

3.4 Palladium-catalyzed ketone arylation reactions

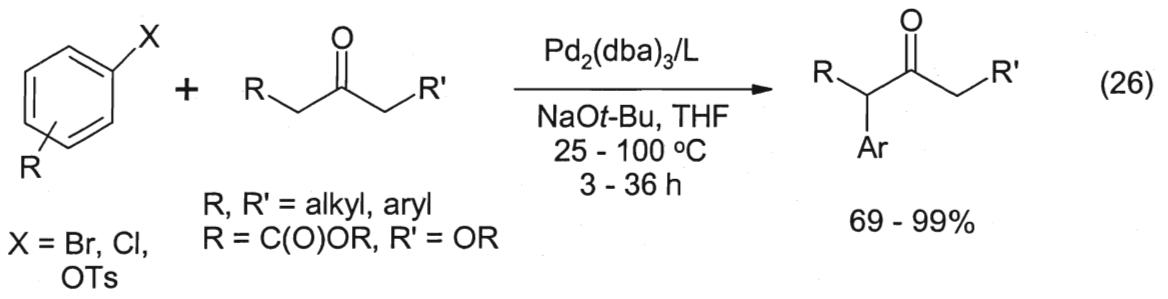
The synthesis of α-aryl ketones has received much attention over the past two and half decades.[64] A number of stoichiometric arylating reagents have been successfully developed for this purpose; however, their utility is decreased because each synthesis of

an α-aryl ketone requires the synthesis of a different arylating reagent.[65] In contrast, the direct coupling of aryl halides with ketones provides a convenient method for the synthesis of α-aryl ketones. In 1975, Semmelhack and co-workers have demonstrated that $Ni(COD)_2$ (COD = cyclooctadiene) catalyzes the intramolecular coupling of an aryl iodide with a ketone enolate. [66] Since then, there have been reports of Pd- or Ni-promoted intermolecular coupling reactions that afford α-aryl ketones. These methods require the use of stoichiometric amounts of tin reagents and/or the use of enol ether, enamine, or α–chloro ketone derivatives instead of the ketone.[65] It was not until 1997, that Buchwald and Palucki described a novel Pd-catalyzed method for the direct cross-coupling of aryl halides with ketones.[65] These researchers found that the combination of $Pd_2(dba)_3$ and Tol-BINAP or BINAP ligand in the presence of NaO^tBu effectively catalyzes the desired coupling reaction, (equation 25).



This remarkable observation has paved the way for renewed interest in the Pd-catalyzed direct α-arylation of ketones and other carbonyl compounds. Hartwig and co-workers reported the coupling of ketones and aryl bromides or iodobenzene with Pd/1,1'-bis (di-o-tolylphosphino)-ferrocene.[67] More recently, the Yale group has disclosed that aryl chlorides, bromides, and (in one case) an aryl tosylate could be coupled with ketone enolates or malonate esters using tri-(tert-butyl)phosphine, (1,1'-bis-(di-tert-

butylphosphino)-ferrocene), D^{t}BPF or 1-diphenylphosphino-2-(di-tert-butylphosphino)-ethylferrocene; PPF-*t*-Bu_2 (equation 26).[68]



(26)

Hartwig's group has also reported catalytic systems for the formation of α-aryl amides, α-arylcyanoacetates, esters, and α-amino esters.[68] Additionally, Miura and co-workers have shown that $PdCl_2$ is an effective catalyst for the arylation of benzyl ketones.[69]

Buchwald and co-workers have made tremendous advances in this field. In 2000, the Buchwald's group has reported that bulky, electron-rich phosphine ligands with a biphenyl backbone, when combined with $Pd(OAc)_2$, give highly active catalysts for the α-arylation of ketones.[70] The group demonstrated that the ligand 2-methyl-2'-dicyclohexylphosphinobiphenyl is particularly effective, and with 0.1 – 1.0 % Pd, a large variety of aryl halides and ketones react efficiently and with high selectivity. In the following year, this group reported an improved catalyst for the asymmetric arylation of ketone enolates.[71] The MIT group claimed that the catalyst prepared from $Pd_2(dba)_3$ and a bulky dialkylphosphino-binaphthyl ligand, is able to effect the asymmetric arylation of ketone enolates with aryl bromides utilizing NaO^{t}Bu as base.

4.0 Phosphine ligands and their role in palladium(0) catalyzed reactions

Many of the important reaction described above are facilitated by palladium complexes incorporationg phosphine ligands. Historically, triphenylphosphine was, by far, the most commonly used ligand for these reaction.[3,72]

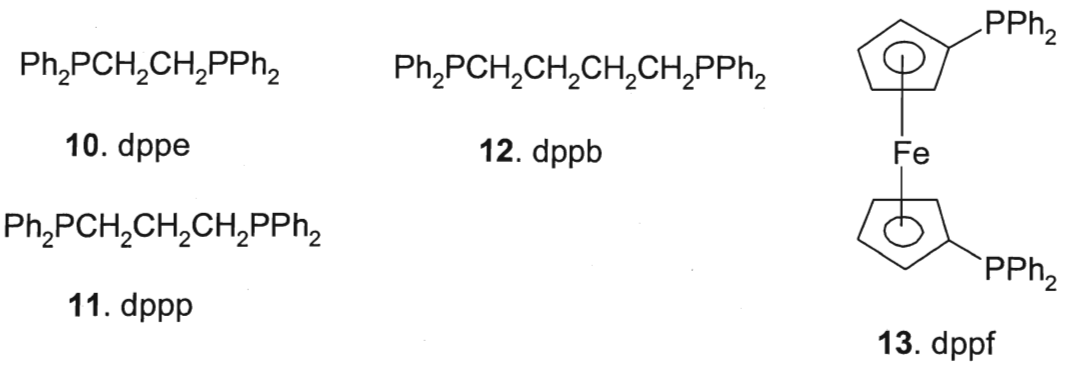


Figure **4**. examples of phosphines used in Pd-catalyzed cross-couplings

However, over the years, a great deal has been learned about the nature of the phosphine ligands in these systems.

As has been illustrated above, more electron-donating alkylphosphines such as tri-*t*-butylphosphine (*t*-Bu_3P), tri-*n*-butylphosphine (n-Bu_3P), triisopropylphosphine (*i*Pr_3P), and tricyclohexylphosphine (Cy_3P)[73,74] or other aryl phosphines such as tri(2,4,6-trimethoxyphenyl)phosphine (TTMPP) and tri(2,6-dimethoxyphenyl)phosphine (TDMPP) have been used to greater effect.[3,75] Bidentate phosphines such as dppe (**10**), dppp (**11**), and dppb (**12**) play important roles in many reactions.[76] Another bidentate phosphine is dppf (**13**), which is different from other bidentate phosphines, showing its own characteristic activity.[3]

Much work has been undertaken in an effort to determine the exact role of these bulky, electron-rich phosphines in palladium-catalyzed coupling reactions. Palladium-

catalyzed cross coupling is commonly proposes to involve 14-electron, three-coordinate complexes.[71a,71b,40] Three-coordinate, 14-electron palladium(II) complexes are believed to be favoured when the catalyst possess sterically hindered ligands.[71c,71d,78] The first case of isolated three-coordinate, 14-electron palladium(II) complexes was reported by Hartwig and co-workers. The authors reported the synthesis, characterization, and reactivity of monomeric, arylpalladium(II) halide complexes with a hindered phosphine. This remarkable pieces of work affirms the suggestions made by other researchers that the monophosphine palladium(0) complex is the active species involved in the oxidative addition step when bulky, electron-rich phosphine ligands are employed.[40] The proposed catalytic cycle for this bulky ligands is depicted in figure 5 below.[77e]

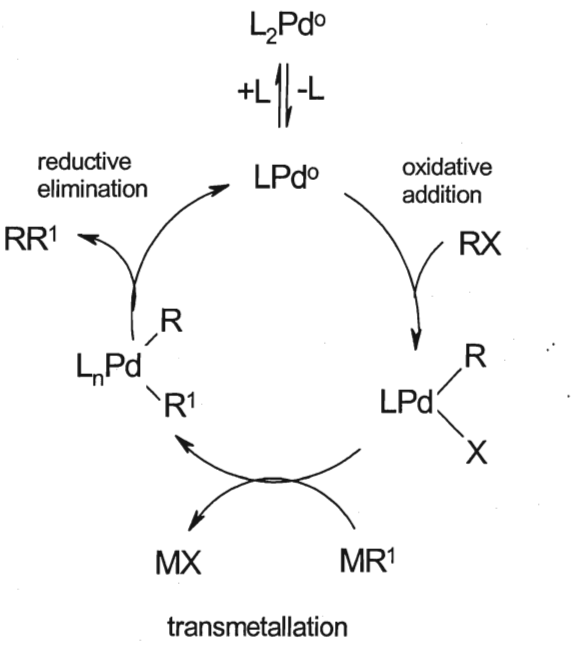


Figure **5**. Generalised mechanism for Pd-catalyzed cross coupling reactions with bulky phosphine ligands.

5.0 Novel class of tertiary phosphine ligands incorporating a phospha-adamantane framework.

Despite the great advances made in palladium-catalyzed cross-coupling chemistry as a result of the utilization of bulky, electron-rich phosphine ligands, several drawbacks associated with these systems still exist. Many of the most effective trialkylphoshines (*t*-Bu_3P and Cy_3P, especially) are prone to oxidation and, as a result, require special conditions for their handling and use. Furthermore, the cost of these compounds can be prohibitive (for example, $30,000 US and $6,000 per kilo for *t*-$Bu_3P$ and Cy_3P, respectively (Aldrich Catalogue). Finally, few "all-in-one" systems are available; convenient palladium-ligand complexes that can be used directly as catalysts are highly desired. In an effort to address these issues, a research program concerned with the development of new, sterically demanding and electron-rich ligands for use in transition-metal catalysis is currently operating within the Capretta laboratories.

Work in the present thesis has focused on the 1,3,5,7-tetramethyl-2,4,8-trioxa-6-phospha-adamantane system. First described by Epstein and Buckler,[79] the phospha-adamantane **14** (figure 6) is a white crystalline solid readily prepared via the condensation of PH_3 with 2,4-pentanedione under acidic conditions (reaction mechanism is presented in Figure 6). The reaction has since seen a number of modifications including the use of fluorine-containing diones[80] and the synthesis of bis(phospha-adamantyl)alkanes from diprimary phosphines.[81]

The phospha-adamantane architecture contains many desirable elements that should be included in a ligand suitable for organopalladium chemistry. While phosphines incorporating an adamantane motif have been used previously in organopalladium

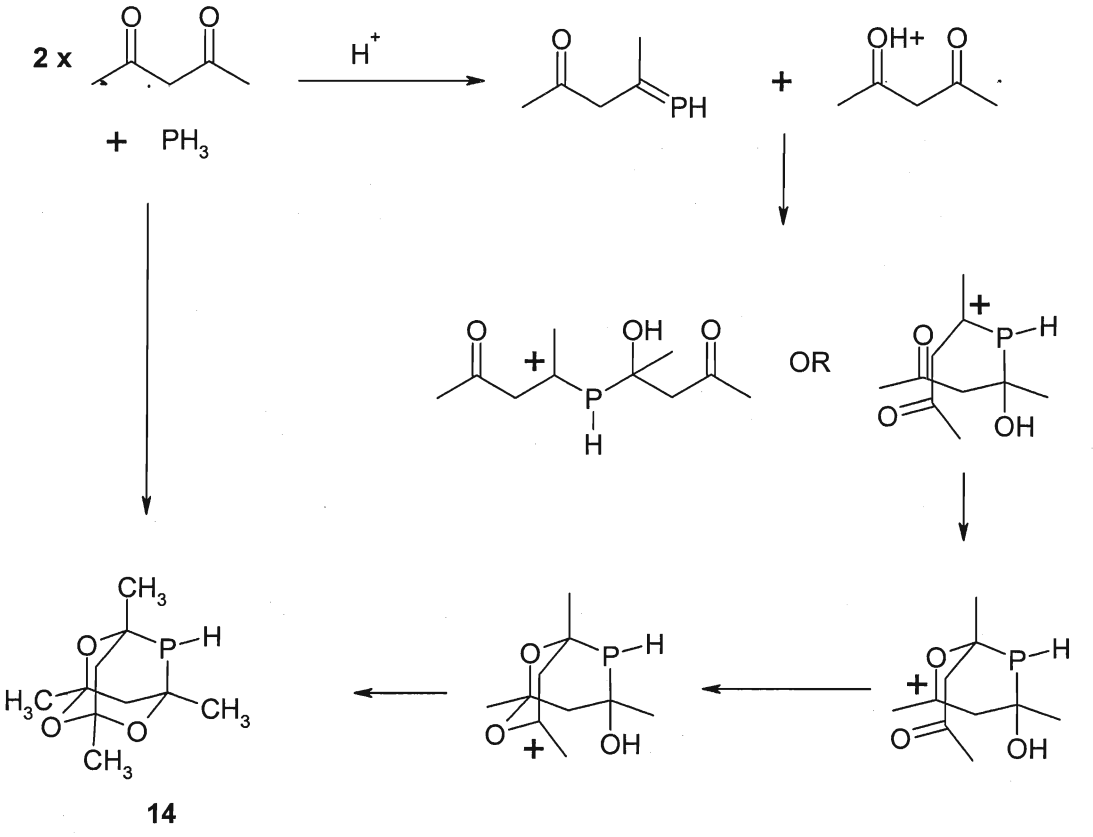


Figure 6. Reaction mechanism for the synthesis of compound **14**.

chemistry, (adamantyldi-tert-butylphosphine, for example),[77,82] systems like **14** have the phosphorous entrenched within the adamantane framework and the inherent steric crowding about the P atom make **14** an ideal architecture for further derivitization to bulky trisubstituted phosphines suitable for use as ligands. This derivitization is necessary because the secondary phosphines are unsuitable for use as ligands.

6.0 Aims and Objectives

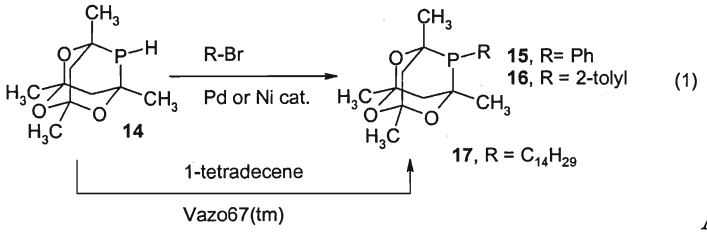
This thesis explores the scope and effective application of the tertiary, air-stable phospha-adamantanes as ligands in selected palladium-catalyzed cross-coupling reactions. This will allow for the generation of a new class of ligands for use in cross-coupling reactions and presents us with a wide range of opportunities to expand on the application of the phospha-adamantane ligands in many other palladium-catalyzed cross-coupling reactions.

Preliminary work was directed towards the generation of suitable tertiary phosphines to act as ligands in the palladium-catalyzed cross-coupling chemistry. With the derivatized phospha-adamantnaes in hand, screening and optimization of these systems in palladium-catalyzed Suzuki cross-coupling reaction of aryl halides with aryl boronic acids was achieved. Palladium complexes of the phospha-adamantanes were prepared, isolated and characterized. These systems were shown to act as effective catalysts for cross-coupling reactions such as the Sonogashira coupling of aryl halides with terminal alkynes and α-arylation of ketones with aryl halides. Advantages of these new systems will be discussed.

RESULTS AND DISCUSSION

1. Tertiary phospha-adamantanes: Novel class of phosphines as ligands for palladium-catalyzed cross-coupling reactions.

As discussed in the introduction, 1,3,5,7-tetramethyl-2,4,8-trioxa-6-phospha-adamantane (PA, **14**) requires further modification to a tertiary phosphine in order to be applied as a ligand for palladium-catalyzed reactions. Chemistry has been developed by researchers at Cytec Canada Inc. that permits the introduction of either aryl and alkyl groups at the phosphorus atom of **14**.



(1)

Arylation of **14** to give phosphines **15** and **16**, for example, has been carried out by treating the secondary phosphine with either bromobenzene or *o*-bromotoluene in refluxing xylene in the presence of either di(μ-acetato)bis[*o*-(di-*o*-tolylphosphino)benzyl] dipalladium(II) or nickel acetate, respectively, as the catalyst. Purified specimens of **15** or **16** were obtained by recrystallization of the crude products from 95% ethanol. X-ray crystal structures of **14**, **15** and **16** with obtained by Dr. Chris Frampton at the University of Southampton and appear in Figures 2, 3 and 4.

Alternatively, alkylation at the phosphorus can be effected *via* a phosphinyl radical addition protocol.[83] Using this procedure, **14** was reacted with 1-tetradecene in the presence of a radical initiator to afford **17**. Unlike the other phospha-adamantanes, **17** is

an oily white solid, which oxidizes slowly when exposed to air. One way to prevent the oxidation of **17** can be achieved by the formation of the air stable phosphonium salt.[78]

Figure 2. Crystal structure for compound **14,** PA-H.

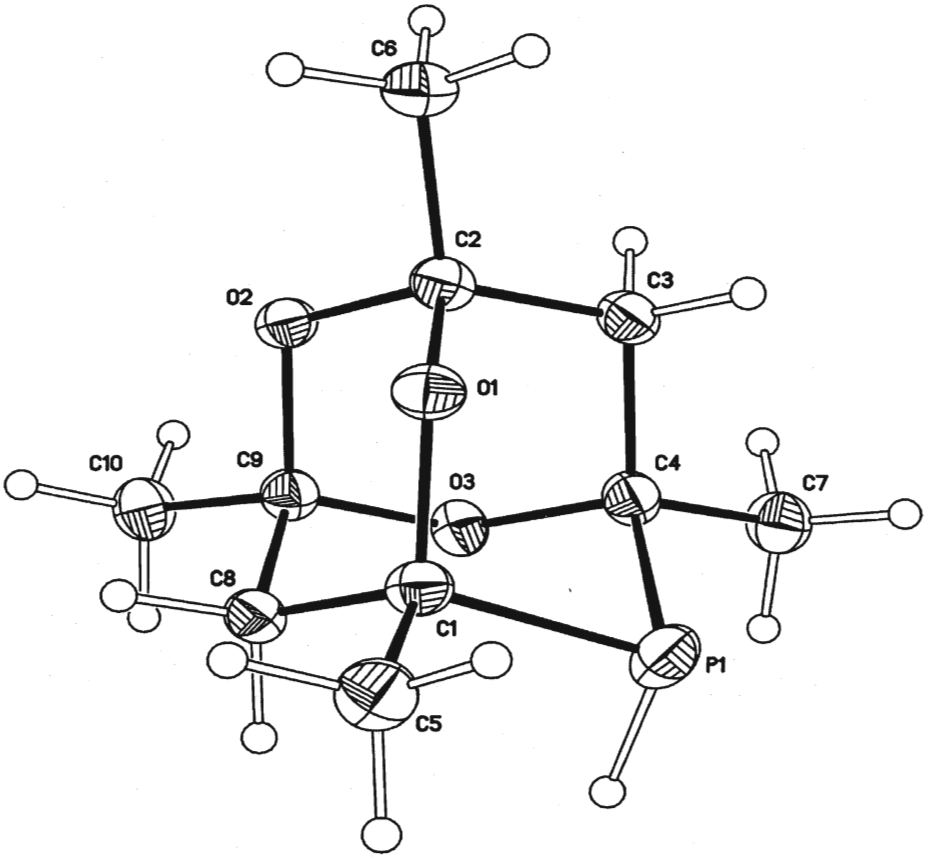


Figure 3. Crystal structure for compound **15,** PA-Ph.

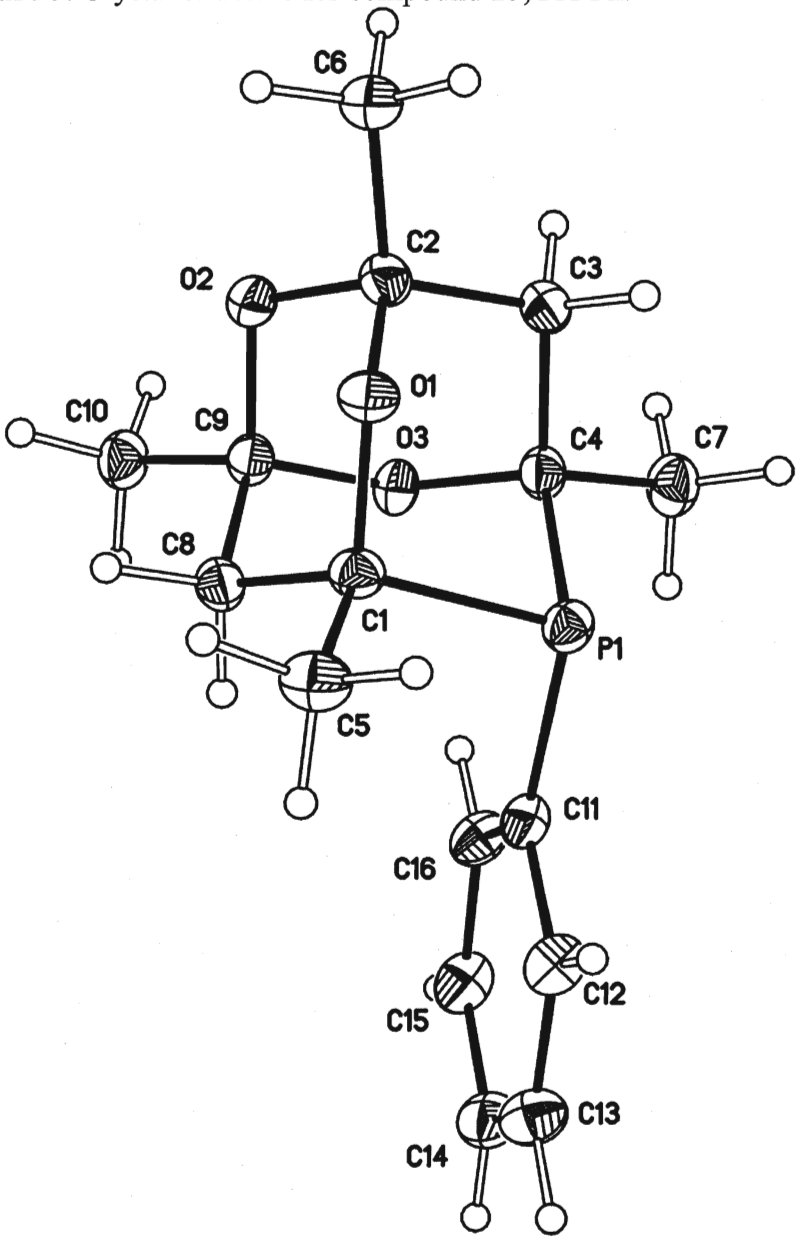
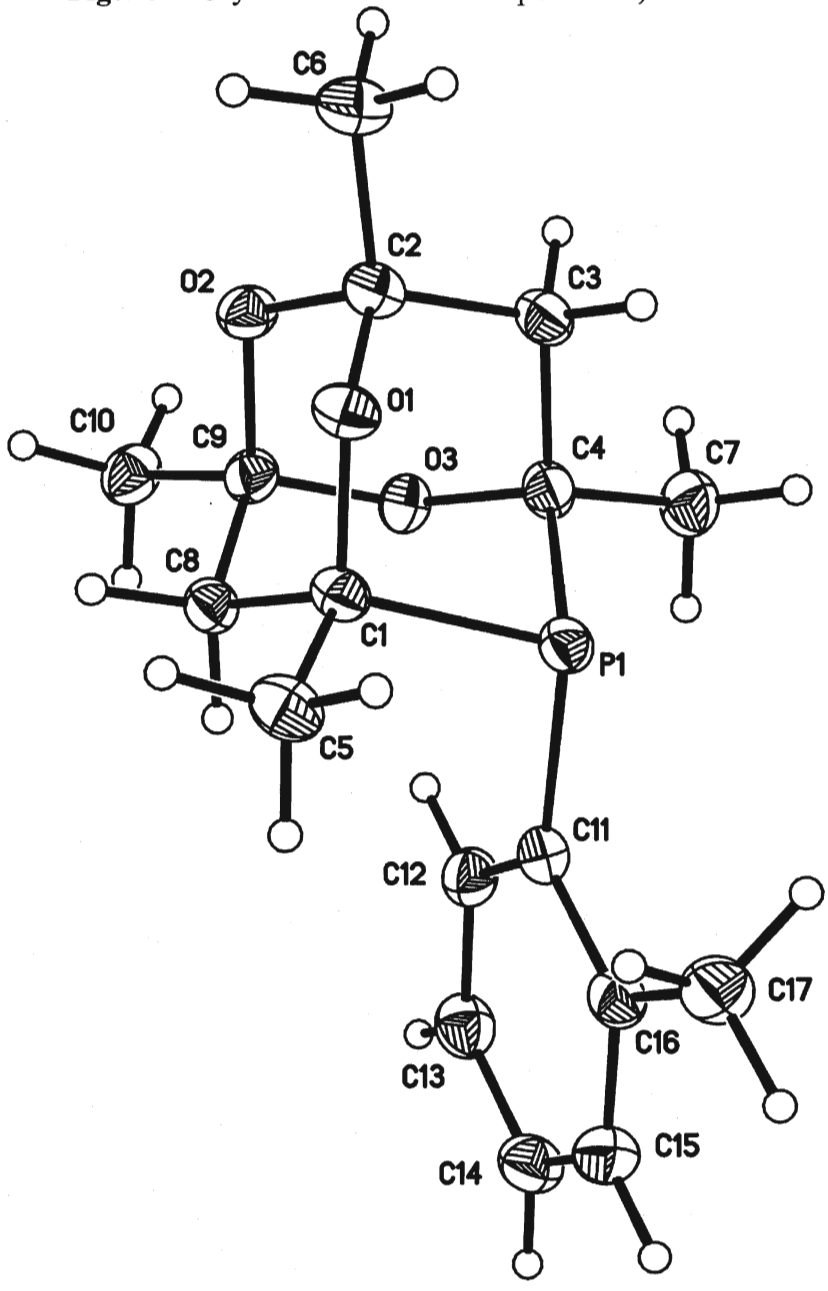
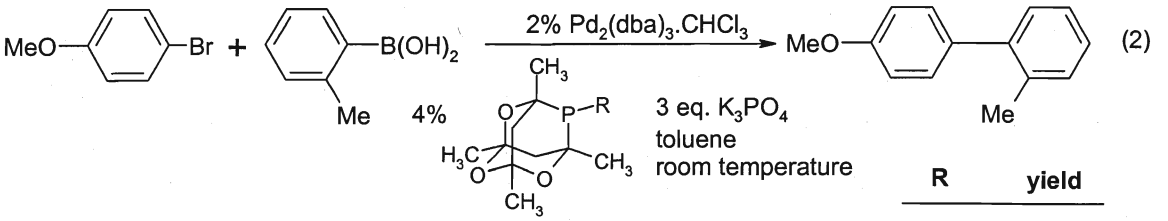


Figure 4. Crystal structure for compound **16,** PA-o-tol



2. Preliminary screening of PA-Ph, PA-o-tolyl and PA-$C_{14}H_{29}$ for Suzuki cross coupling reactions.

With the suitable tertiary phosphines (**15**, **16** and **17** abbreviated as PA-Ph, PA-o-tolyl and PA-$C_{14}H_{29}$ respectively) in hand, attention was then turned to the application of the phospha-adamantanes to palladium-catalyzed cross-coupling reactions. Preliminary screening involved the Suzuki coupling of *p*-methoxybromobenzene and *o*-methylphenylboronic acid (equation 2).



R	yield
Ph	87%
o-tolyl	85%
$C_{14}H_{29}$	80%

There are a number of reaction parameters (including palladium source, additive, solvent, and temperature) that can be varied to ultimately optimize the reaction. In the first instance, 2% $Pd_2(dba)_3.CHCl_3$ and 4% of the tertiary phospha-adamantane were used in addition to 3 equivalents of K_3PO_4 in toluene. Satisfying, all 3 phospha-adamantane ligands were able to effect the Suzuki coupling in roughly the same yield at room temperature.

Optimization of the reaction parameters was then undertaken. To ascertain the best conditions for effective palladium-catalyzed Suzuki reaction, various palladium reagents, additives (bases), and solvents were screened, keeping all reactions at this stage at room temperature. Among the palladium reagents screened, $Pd_2(dba)_3.CHCl_3$ was found to be the palladium source of choice, although $Pd(OAc)_2$ was effectively used in some cases. A

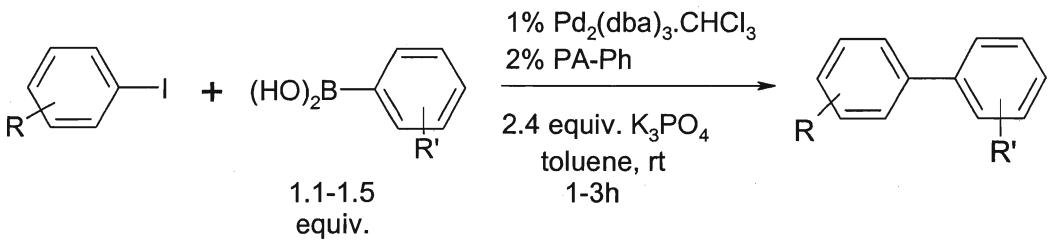
rather wide range of bases were screened, KF, Et_3N, $(i\text{-}Pr)_2NEt$, Et_2NH, K_3PO_4, and Cs_2CO_3. Although pleased with the results from the screening, as all these bases proved effective, potassium phosphate and cesium carbonate gave the best results and were subsequently used for the Suzuki cross-coupling of aryl halides. Potassium phosphate was mostly used and cesium carbonate was only used in cases where the former was found to be less effective (that is reactions that take longer to complete). Toluene was found to be the solvent of choice as other solvents such as THF, dioxane and acetonitrile were less effective. It was also noticed in some cases that addition of water was very effective.

The optimum conditions were achieved when 1:1 ratio of Pd(0) and PA-R were used (although slightly higher ligand loadings were used for the aryl chlorides). The ratio of palladium to phosphine ligand was found to play a very important role in achieving optimum results. For instance, reactions of aryl iodides proceed very sluggishly when 1:2 ratio of Pd(0) to PA-Ph were used. On the other hand, a 1: 2 – 2.5 ratio of Pd(0) to PA-Ph resulted in the effective coupling of aryl chlorides. The exact role of these varying ratios for effective coupling remains unclear. Optimum conditions were used for the screening described below. Finally, it should be noted that since ligand PA-Ph (**15**) gave the best yield and was available in the greatest amount, all the results presented below for the Suzuki cross coupling were carried out using this tertiary phospha-adamantane.

3. Room-Temperature Suzuki Cross-Coupling of Aryl Iodides

Electron-neutral, electron-rich as well as electron-poor aryl iodides were cross-coupled with a wide range of electron-neutral, electron-poor and electron-rich

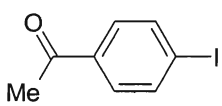
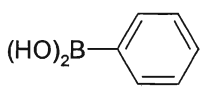
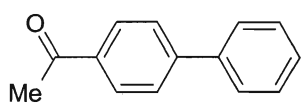
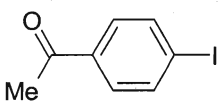
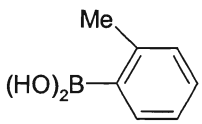
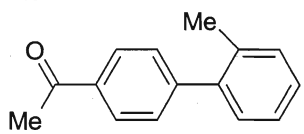
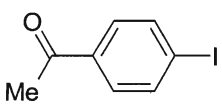
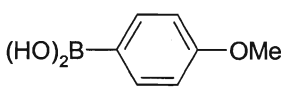
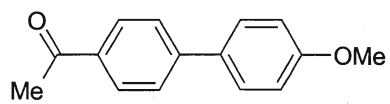
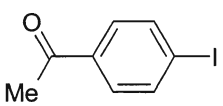
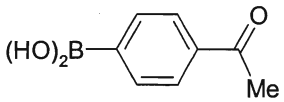
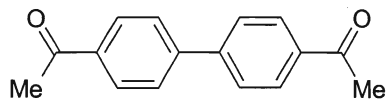
arylboronic acids to afford biaryls in excellent yields (Table 1- 4) (90-98%).



(3)

As mentioned in section 2, a 1:1 $Pd_2(dba)_3.CHCl_3$/ PA-Ph was used. Although lower catalyst loading was effective, 1% $Pd_2(dba)_3.CHCl_3$ was used in all cases unless otherwise noticed.

Table 1. Suzuki cross-coupling of 4-Iodoacetophenone at room temperature.

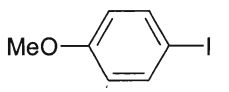
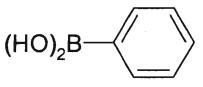
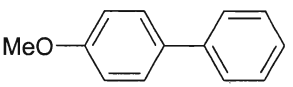
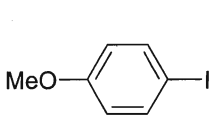
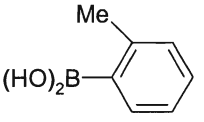
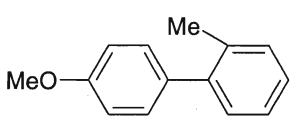
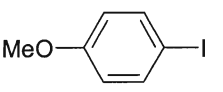
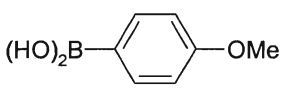
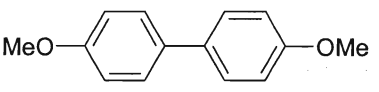
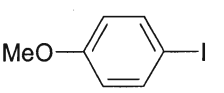
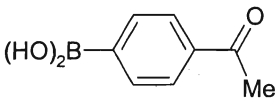
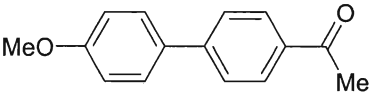
Entry	Aryl Iodide	Arylboronic acid	Product	Yield[a]
1				98%
2				94%
3				96%
4[b]				94%

[a]Isolated yield, [b]trace amounts of THF and water were added, 3% PA-Ph used and reaction carried out at 40°C.

Aryl iodides are usually the most reactive aryl halides in palladium-catalyzed

reactions. Suzuki cross-coupling of 4-iodoacetophenone (activated aryl iodide) with an array of electronically diverse arylboronic acids proceeded smoothly as expected to give excellent yields (Table 1; 94-96%). For instance, 4-iodoacetophenone reacted cleanly with sterically hindered *o*-tolylboronic acid (entry 2, Table 1). The best coupling partners for Suzuki cross-coupling of aryl halides with arylboronic acids are activated aryl halide (activated towards oxidative addition) and deactivated arylboronic acid (activated towards transmetallation), respectively. A representative example in this case is the coupling of 4-iodoacetophenone with 4-methoxyphenylboronic acid (entry 3, Table 1). Even so, cross-coupling of 4-iodoacetophenone with 4-acetylboronic (highly deactivated towards transmetallation) proceeded smoothly, although the reaction condition was slightly altered (entry 4, Table 1).

Table 2. Suzuki Cross-Coupling of 4-Iodoanisole at Room-Temperature.

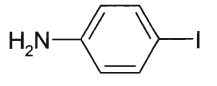
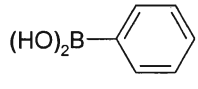
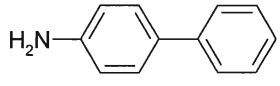
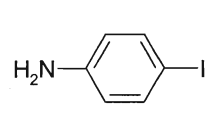
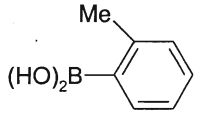
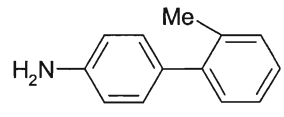
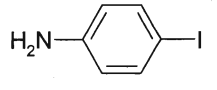
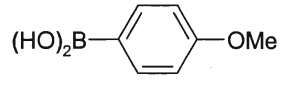
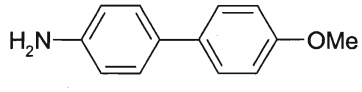
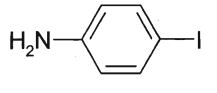
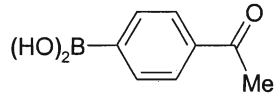
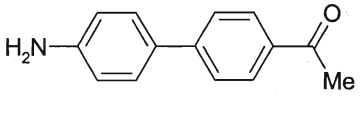
Entry	Aryl Iodide	Arylboronic acid	Product	Yield[a]
1				98%
2				90%
3				97%
4[b]				94%

[a]Isolated yield, [b]small amounts of THF and water were added, 3% PA-Ph was used and reaction carried out 40°C.

Room-temperature Suzuki cross-coupling of deactivated 4-iodoanisole with various

arylboronic acids was successfully achieved in excellent yields (Table 2; 90 – 98%). As a reprepresentative example, note that 4-iodoanisole (deactivated towards oxidative addition) cross-coupled cleanly with 4-acetylboronic acid in excellent yield (entry 4, Table 2). Addition of small amounts of water and THF (entries 4, Table 1 - 4) appeared to help promote the reaction. The role of THF was to maintain solubility of 4-acetylboronic acid, which is not readily soluble in toluene. 4-Iodoanisole was cross-coupled with o-tolylboronic acid to give excellent yield (entry 2, Table 2).

Table 3. Room-Temperature Suzuki Cross-Coupling of 4-Iodoaniline.

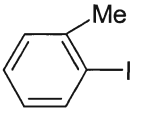
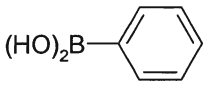
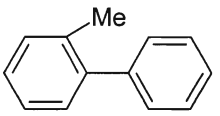
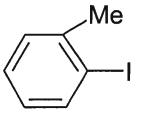
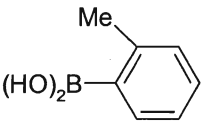
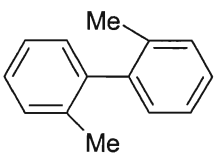
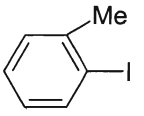
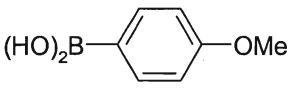
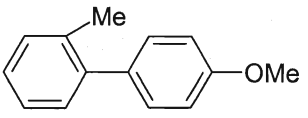
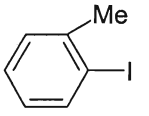
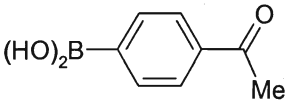
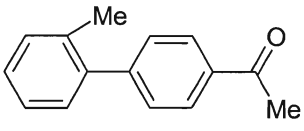
Entry	Aryl Iodide	Arylboronic acid	Product	Yield[a]
1				96%
2				96%
3				94%
4[b]				92%

[a]Isolated yield, [b]small amounts of THF and water were added, 3% PA-Ph was used and reaction carried out 40°C.

4-Iodoaniline, an electron-rich aryl iodide, reacted with various arylboronic acids to afford excellent results (Table 3; 92 – 98%). As mentioned in the discussion of the results in Tables 1 and 2, 4-iodoaniline, cross-coupled with sterically hindered o-tolylboronic (entry 2, Table 3), and electron-poor 4-acetylboronic acid coupled effectively with 4-iodoaniline (entry 4, Table 3). 4-Iodoaniline, which is normally a poor partner for Suzuki

cross-coupling due in part to its electron-richness (deactivated towards oxidative addition), reacted smoothly with sterically hindered o-tolylboronic acid to afford excellent yield (entry 2, Table 3).

Table 4. Room-Temperature Suzuki Cross-Coupling of 4-Iodotoluene.

Entry	Aryl Iodide	Arylboronic acid	Product	Yield[a]
1				97%
2				98%
3				93%
4[b]				96%

[a]Isolated yield, [b]THF was used as cosolvent, 3% PA-Ph was used and reaction was carried out at 40 °C.

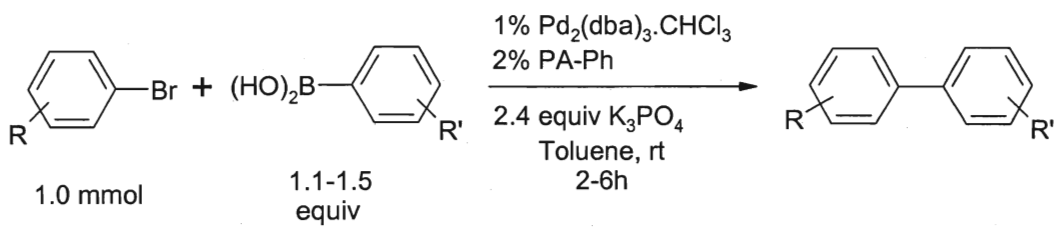
Electronically diverse arylboronic acids couple efficiently with sterically hindered 2-iodotoluene (Table 4). Di-*ortho*-substituted biaryls are also readily obtained in excellent yield (entry 2, Table 4).

During the cross-coupling of aryl iodides, it was noticed that the use of excess ligand slows down the reaction with the exception of reactions involving 4-acetylboronic acid, where 1:1.5 ratio of Pd: PA-Ph was used. For instance, using a 1:1 Pd/PA-Ph the cross-coupling of 4-iodoacetophenone with phenylboronic acid (entry 1, Table 1), takes

approximately one hour to complete, whereas using 1:2.5 Pd/PA-Ph, it took more than three hours for the same reaction to be completed. As observed for the reactions involving 4-acetylboronic acid, addition of a small amount of THF to keep the boronic acid soluble resulted in the coupling of 4-acetylboronic acid with various aryl iodides to give excellent yields (entry 4, Tables 1-4). In the absence of PA-Ph ligand, no cross-coupling occurred between 4-iodoanisole and o-tolylboronic at room temperature (cf. Table 3, entry 2).

4. Suzuki Cross-Coupling of Aryl Bromides

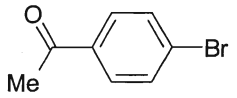
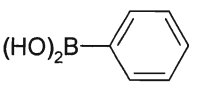
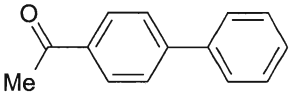
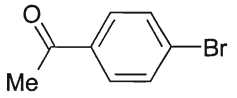
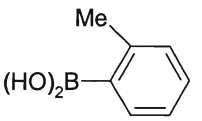
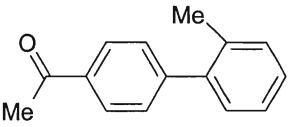
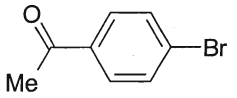
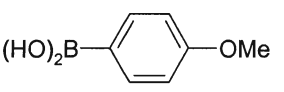
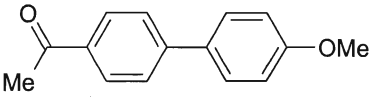
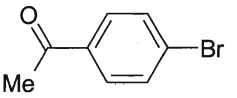
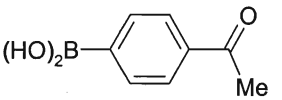
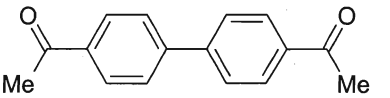
There are relatively few examples of palladium-catalyzed Suzuki cross-coupling of aryl bromides that proceed at room temperature. As a consequence, independent reports by Buchwald and Fu of general methods for accomplishing this process represent a notable advance.



(4)

We have also determined that we can effect room-temperature Suzuki cross-couplings of a broad spectrum of aryl bromides and arylboronic acids using $Pd_2(dba)_3$/PA-Ph catalyst systems. As illustrated in Tables 5 – 8, this catalyst furnishes the desired biaryls in excellent yields (93 – 100%). In contrast to their iodo counterparts, however, the coupling of aryl bromides proceeds to completion in 3 - 6h.

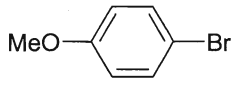
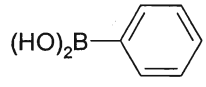
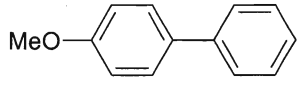
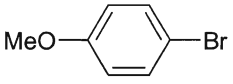
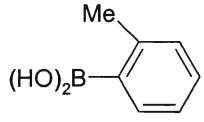
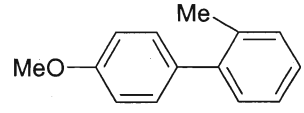
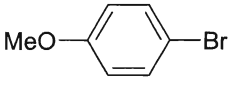
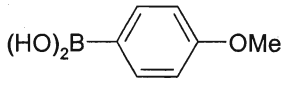
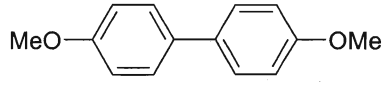
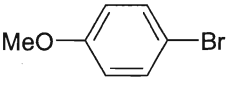
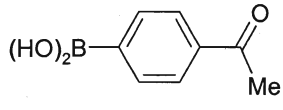
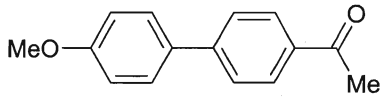
Table 5. Room-Temperature Suzuki Cross-Coupling of 4-Bromoacetophenone

Entry	Aryl Bromide	Arylboronic acid	Product	Yield[a]
1				99%
2				97%
3				99%
4[b]				95%

[a]Isolated yield, [b]trace amounts of THF and water were added, 3% PA-Ph used and reaction carried out at 40°C.

The Suzuki cross-coupling of 4-bromoacetophenone with electron-neutral, electron-rich and electron-poor arylboronic acids proceed smoothly to give excellent isolated yields of various biaryls (Table 5). The $Pd_2(dba)_3$/PA-Ph catalyst system is very tolerant of electronic variations in the arylboronic acid component. The results obtained in Table 5 for the cross-coupling of 4-bomoacetophenone indicate slightly higher yields (average yield, 98%) than observed for the cross-coupling of 4-iodoacetophenone (Table 1, average yield, 96%), probably due to higher purity of 4-bromoacetophenone.

Table 6. Room-Temperature Suzuki Cross-Coupling or 4-Bromoanisole.

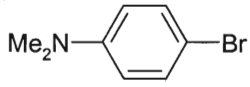
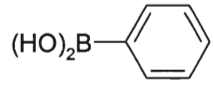
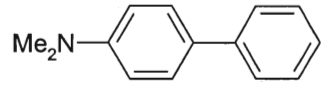
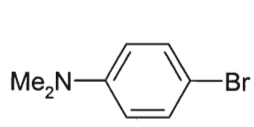
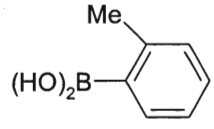
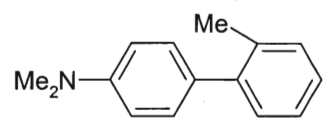
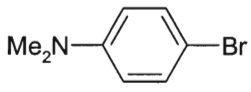
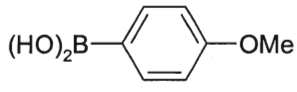
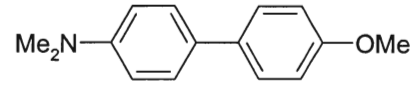
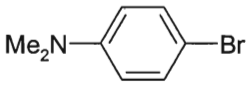
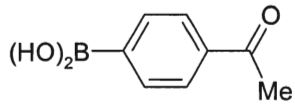
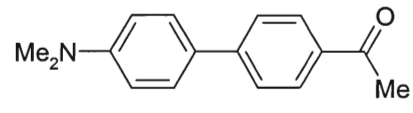
Entry	Aryl Bromide	Arylboronic acid	Product	Yield[a]
1				97%
2				95%
3				98%
4				94%

[a]Isolated yield, [b]small amounts of THF and water were added, 3% PA-Ph was used and reaction carried out 40°C.

Suzuki cross-coupling of electron-rich 4-bromoanisole, with a diverse range of electron-rich, electron-poor and electron-neutral arylboronic acids proceed in excellent yields (94-98%). Thus, 4-bromoanisole coupled cleanly with electron-poor 4-acetylboronic acid (entry 4, Table 6).

The reactions of very electron-rich 4-bromo-*N,N*-dimethylaniline (Table 7) with an array of electronically diverse arylboronic acids, that proceed to completion within 6 hours are particularly noteworthy. Even the most difficult cross-coupling partners (entry 4, Table 7), cross-coupled smoothly at 40°C with slight modification of conditions. Initial difficulties encountered during the cross-coupling of these partners at room-temperature is indicative of the unreactive nature of 4-bromo-*N,N*-dimethylaniline with 4-acetylboronic acid.

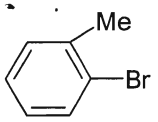
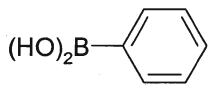
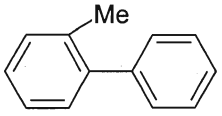
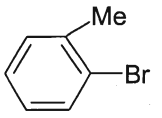
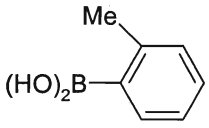
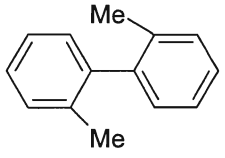
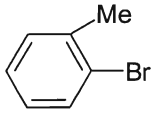
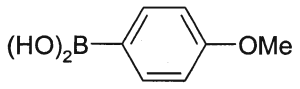
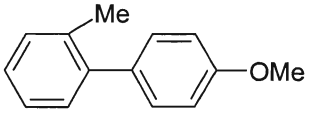
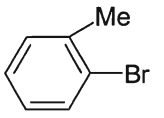
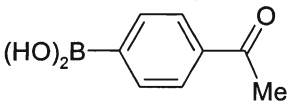
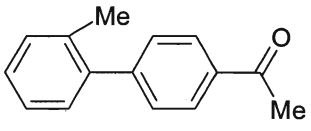
Table 7. Room-Temperature Suzuki Cross-Coupling of 4-Bromo-*N,N*-dimethylaniline.

Entry	Aryl Bromide	Arylboronic acid	Product	Yield[a]
1				94%
2				97%
3				96%
4[b]				93%

[a]Isolated yield, [b]small amounts of THF and water were added, 3% PA-Ph was used and reaction carried out 40°C.

Finally, the $Pd_2(dba)_3$/PA-Ph catalyst system allows for the Suzuki coupling of even the more sterically demanding arylhalides. For example, 2-bromotoluene reacts cleanly at room-temperature with electron-poor, electron-neutral, and electron-rich boronic acids (entries 1-4, Table 8). Di-ortho-substituted biaryl, 2,2'-dimethylbiphenyl was obtained in excellent yield (entry 2, Table 8) within 6 h at room-temperature.

Table 8. Room-Temperature Suzuki Cross-Coupling of 2-Bromotoluene.

Entry	Aryl Bromide	Arylboronic acid	Product	Yield[a]
1				98%
2				100%
3				98%
4[b]				96%

[a]Isolated yield, [b]THF used as cosolvent, 3% PA-Ph was used and reaction was carried out at 40°C.

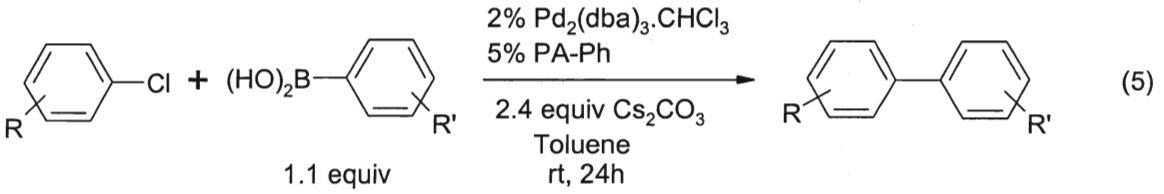
5. Suzuki Cross-Coupling of Aryl Chlorides

As discussed in the Introduction, one of the most important limitations of the Suzuki cross-coupling reaction was the poor reactivity of aryl chlorides (the most attractive family of aryl halide substrates due to their low cost and their ready availability). In fact, prior to 1998, reports of efficient palladium-catalyzed Suzuki couplings of aryl chlorides were limited to reactions of activated substrates (*i.e.*, heteroaryl chlorides and aryl chlorides that bear an electron-withdrawing group), which generally only proceeded at high temperature (75-130 °C). Since 1998, several research groups have described electron-rich ligands for palladium that overcome this limitation, specifically, aryldialkylphosphines (Buchwald, Bei and Guram), $P(tBu_3)_3$ (Fu), and N-heterocyclic carbenes (Nolan, Herrmann). With respect to Suzuki cross-couplings of aryl chlorides that proceed at room temperature, the only successful catalyst systems reported

to date are those of Buchwald, Fu and Kocovsky (one example).[11]

In our studies, we discovered a general method for the Suzuki cross-coupling of activated aryl chlorides at room temperature and quickly observed that we could cross-couple unactivated aryl chlorides at higher temperatures (60-70 °C). To date, only Richards and co-workers reported successful Suzuki cross-coupling of unactivated aryl chloride at 60 °C. Prior to this report, the lowest temperature was 70 °C, reported by Fu and co-workers.

Thus, our catalyst system constitutes one of the most effective catalyst systems discovered to date. A $Pd_2(dba)_3$/PA-Ph catalyst system, with Cs_2CO_3 as the base and toluene as the solvent was effectively used to cross-couple activated aryl chlorides at room temperature to afford good to excellent yields within 24 h (entry 1-5, Table 9). Thus, 2-chloropyridine cross-couples efficiently with electron-neutral, with sterically hindered, and electron-rich arylboronic acids (entries 1-3, Table 9). Also 2-chlorobenzonitrile couples cleanly with sterically hindered o-tolylboronic acid at room temperature (entry 4, Table 9).

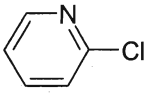
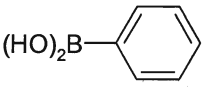
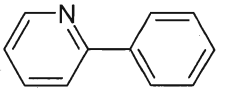
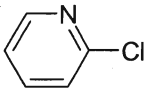
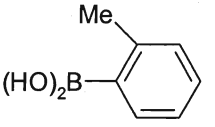
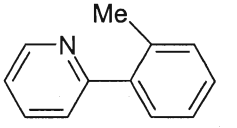
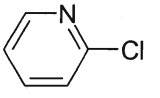
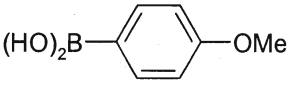
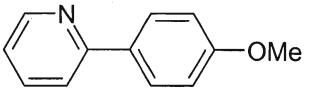
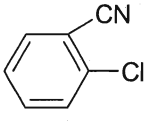
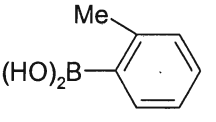
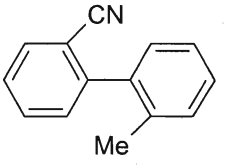
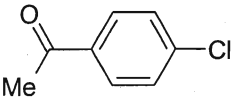
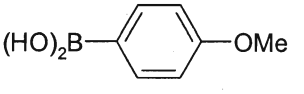
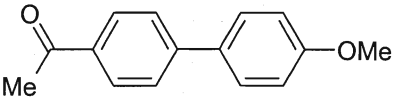
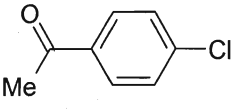
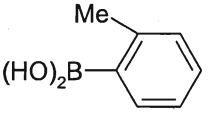
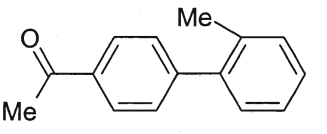


(5)

More vigorous conditions are typically required to effect Suzuki cross-couplings of electron-neutral and electron-rich aryl chlorides (70-100 °C). To find a catalyst system that is effective at the cross-coupling of these otherwise less reactive substrates at lower temperatures (60-70 °C) is worth mentioning. Thus 4-chlorotoluene cross-couples

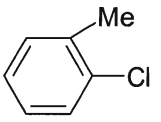
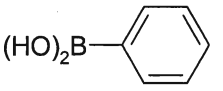
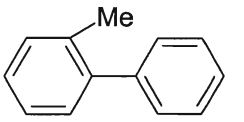
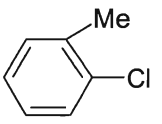
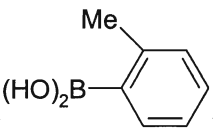
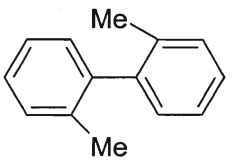
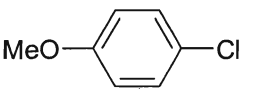
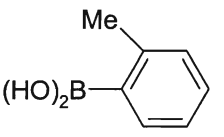
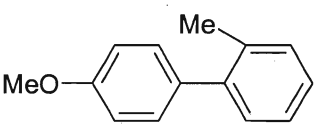
efficiently with phenylboronic acid and sterically hindered o-tolylboronic acid to afford mono- and di-ortho-substituted biaryls in excellent yields at 60 °C (entries 1-2, Table 10). An efficient Suzuki cross-coupling of electron-rich 4-chloroanisole with o-tolylboronic acid was achieved in excellent yield at 70 °C (entry 3, Table 10).

Table 9. Room-Temperature Suzuki Cross-Coupling of Activated Aryl Chlorides

Entry	Aryl Chloride	Arylboronic acid	Product	Yield[a]
1[b]				92%
2				90%
3				89%
4				70%
5[c]				92%
6[d]				100%

[a]Isolated yield, [b]GC taken after 16 h at rt gave 100% conversion, [c]5% $Pd(OAc)_2$ and 10% PA-Ph were used. [d]GC yield (total conversion, no peak observed for starting material).

Table 10. Suzuki Cross-Coupling of Unactivated Aryl Chlorides

Entry	Aryl Chloride	Arylboronic acid	Product	Yield[a]
1[b]				88%
2				93%
3[c]				96%

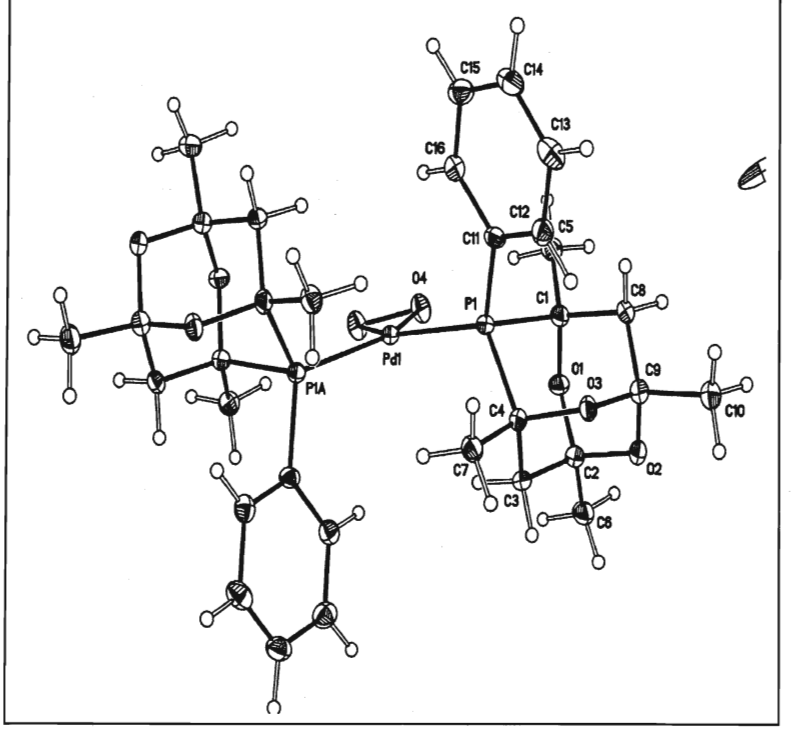
[a]Isolated yield, [b]4% $Pd(PA\text{-}Ph)_2$-dba was used to obtain over 90% conversion. [c]Reaction was carried out at 70°C.

Overall, as the results above demonstrate that palladium complexes derived from ligand **15** are very active in the Suzuki cross-coupling of aryl halides including difficult aryl chlorides. Furthermore, the ligands based on our phospha-adamantane framework are advantageous in comparison to the other phosphines currently employed in palladium mediated cross-coupling chemistry. Many of the best ligands, such as $P(t\text{Bu})_3$ for example, are generally expensive and prone to rapid oxidation often requiring special conditions for their handling. In contrast, the aryl-substituted phospha-adamantanes are crystalline, air stable and relatively inexpensive to manufacture. Ligand **2** matches $P(t\text{Bu})_3$ with respect to coupling conditions and yields in the Suzuki reaction. The ligand can be recovered by chromatography on silica gel and reused. In addition, the syntheses of new ligands based on **14** allow for incorporation of substituted aryl or alkyl groups onto the phosphorus allowing for steric and electronic fine tuning of the ligand.

6. Synthesis and screening of palladium complexes of 1, 3, 5, 7-tetramethyl-2, 4, 8-trioxa-6-aryl-6-phospha-adamantanes.

During the course of our studies of the $Pd_2(dba)_3$/PA-Ph catalyst system, we discovered that the bisphosphine-palladium(0) complex could easily be synthesised by simply stirring $Pd_2(dba)_3.CHCl_3$ and PA-Ph in toluene (or hexane) at room-temperature. The bisphosphine-palladium complex is obtained in almost quantitative yield but crystallizes as two forms: "brown-green needle-like crystals" and "light green micro crystals". While both forms are air and moisture stable, the former normally forms first and in larger quantity than the latter. Complete characterization of the complexes was achieved using ^1H NMR and ^{13}C NMR spectroscopy. NMR revealed that the brown crystals contained a dibenzylideneacetone (dba) moiety in addition to the phospha-adamantane fragment. Integration of the A-B quartet of the dba and the methyl groups on the phospha-adamantanyl moieties enabled us to assign the brown crystalline material as $Pd(PA\text{-}Ph)_2$-dba. In constrast, ^1H- and ^{13}C-NMR revealed that the

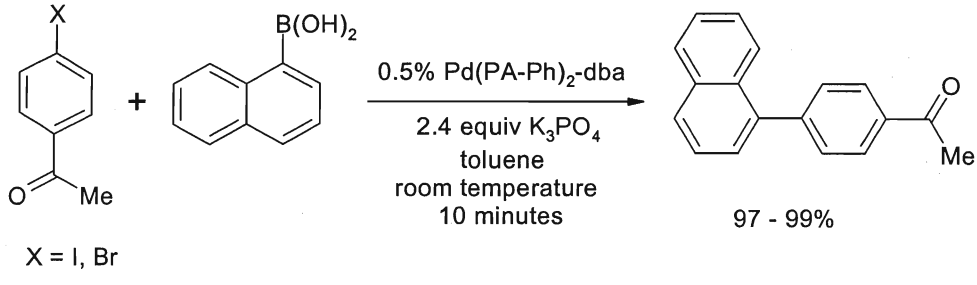
Figure **5**. X-ray structure of $Pd(PA\text{-}Ph)_2O_2$



light green micro crystals do not contain any dba. X-ray crystallographic analysis, however, determined that the light green crystals were, in fact the peroxypalladium complex, $Pd(PA\text{-}Ph)_2O_2$ (figure 4).

Some interesting features of these palladium complexes deserve mention. First of all, in the ^{1}H-NMR of $Pd(PA\text{-}Ph)_2$-dba the chemical shifts of the olefin protons of dba were clearly visible as an AB-quartet at 7.76 and 7.11 ppm and indicate that the dba is not coordinated with the Pd in solution. Contrast these chemical shifts with those reported by Stahl and co-workers wherein their (bathocupronine)Pd(η^2-dba) showed an AB-quartet for the coordinated olefin protons at δ 4.47 and 4.24 ppm.[84] The dissociation of the dba from the palladium in $Pd(PA\text{-}Ph)_2$-dba in solution opens two vacant co-ordination sites on the palladium (presumably occupied by solvent) to give a $Pd(PA\text{-}Ph)_2$ species. With the coordinated dba ligand displaced, the $Pd(PA\text{-}Ph)_2$ is ready to undergo its first oxidative addition. It should be noted that crystals of $Pd(PA\text{-}Ph)_2$-dba are air stable and do not convert to the peroxo form.

The catalytic activity of the complexes was then determined. Satisfyingly, Suzuki cross-coupling of 4-bromoacetophenone with 1-naphthalene boronic acid using the $Pd(PA\text{-}Ph)_2$-dba system revealed extraordinary activity. This reaction was completed within ten minutes with catalyst loadings as low 0.5%. Similar result was obtained for the cross-coupling of 4-iodoacetophenone with 1-naphthalene boronic acid (equation 6).

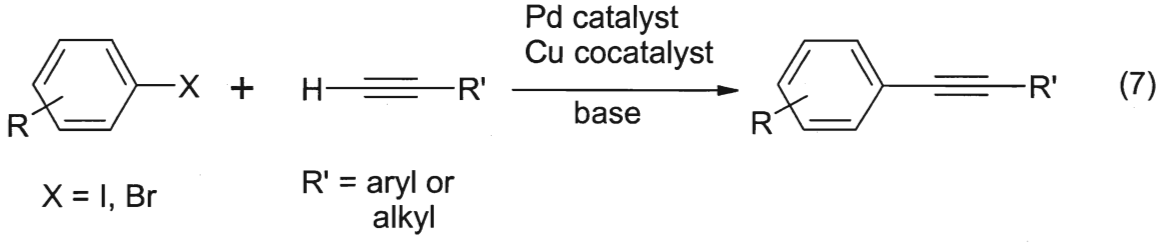


(6)

Interestingly, Pd(PA-Ph)$_2$–dba could be used to obtain 90% conversion for the cross-coupling of 2-chlorotoluene with phenylboronic acid at a slightly milder temperature (60 °C) than previously obtained. Another screening result worth mentioning was the reaction of the sterically hindered 2,4,6-mesitylbromide with 1-naphthalene boronic acid to afford over 85% conversion (^{1}H NMR: ratio of product to unreacted aryl bromide) at room temperature. Furthermore, initial screening of both the Pd(PA-Ph)$_2$-dba and Pd(PA-Ph)$_2$O$_2$ revealed that the former is the more active catalyst with the latter system requiring heating to carry out the palladium-catalyzed coupling reactions (see section 8). This is not surprising since the Pd(PA-Ph)$_2$O$_2$ (Pd(II) species) needs to undergo a reductive elimination of O_2 before the active Pd(PA-Ph)$_2$ species is liberated and can undergo its first oxidative addition.

Although pleased with the success of the preliminary screening of the palladium-phopha-adamantane complexes in the Suzuki cross-coupling of aryl halides, our attention was turned to the application of the Pd(PA-Ph)$_2$-dba complex in other cross-coupling reactions.

7. Sonogashira reactions of aryl iodides and bromides.



(7)

Typically, the Sonogashira reaction of terminal alkynes with aryl/vinyl

halides/triflates is catalyzed by palladium and copper co-catalyst system in the presence of an organic base. In the early versions of the reaction, the base acted both as an acid scavenger and reaction medium. The catalytic cycle is illustrated in Figure 5. As can be seen from figure 5, considerable amount of alkyne is lost through homo-coupling in the steps leading from Pd(II) to Pd(0). It is, therefore, highly desirable to employ Pd(0) catalyst systems that will somehow minimise the lost of alkyne. It is believed that CuI forms the copper acetylide, which facilitates transmetallation.

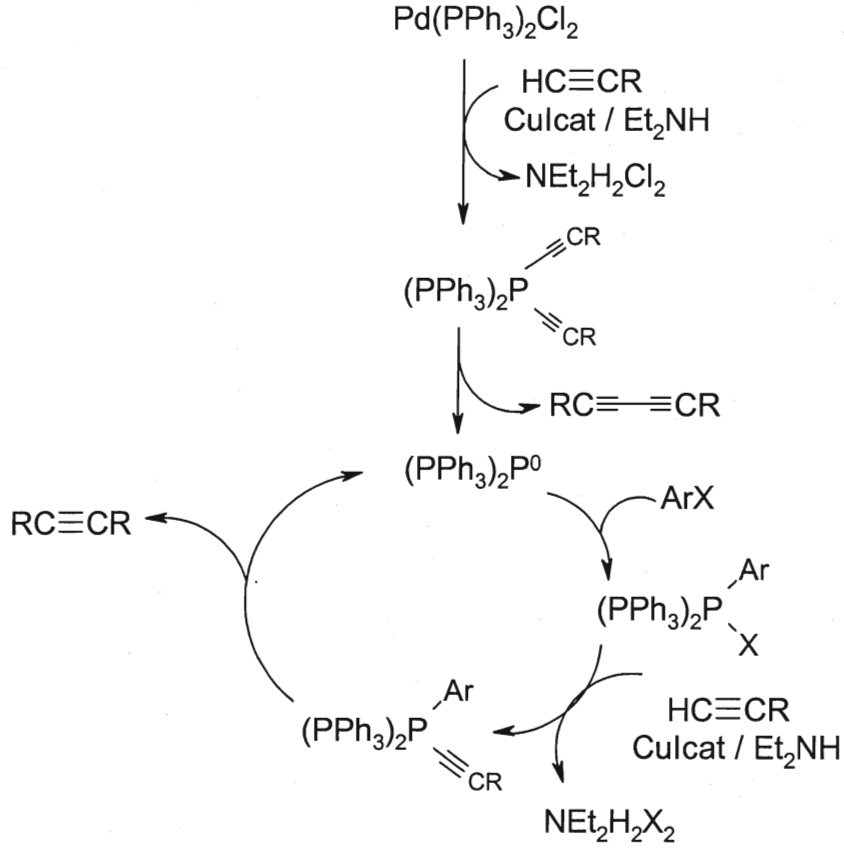


Figure **6**. Proposed mechanism of Sonogashira reaction by Sonogashira.

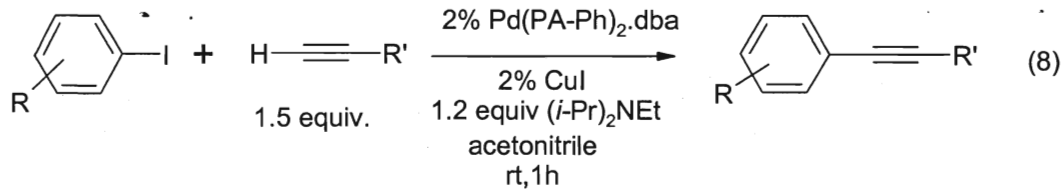
Recently, there have been many reports that carry out the Sonogashira reaction in organic solvents and various organic or inorganic bases are used as additives. Until recently, room temperature Sonogashira reactions were limited to those involving aryl

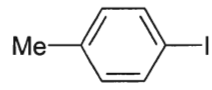
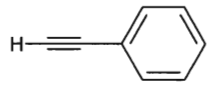
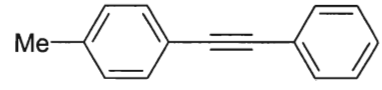
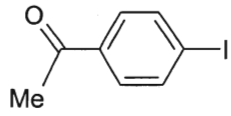
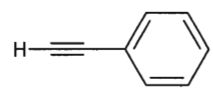
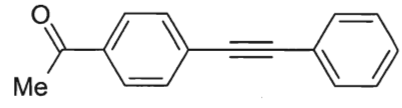
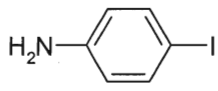
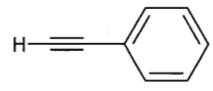
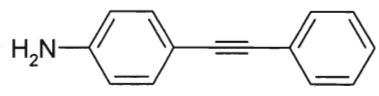
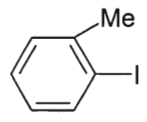
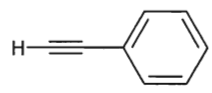
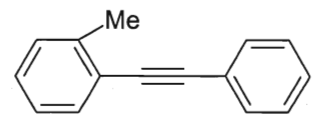
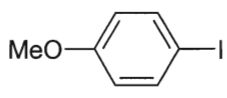
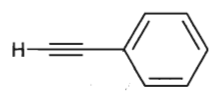
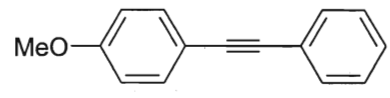
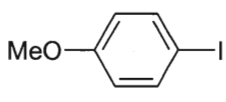
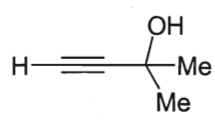
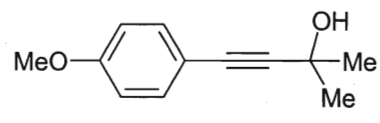
iodides. Aryl bromides are known to be less reactive and require heating at higher temperatures (usually 80 °C and over) to proceed. There is still no general protocol for effective Sonogashira reaction of aryl chlorides. However, there are a few examples of the Sonogashira reaction involving activated aryl chlorides that are coupled at high temperatures (usually 120 °C). In 2000, Fu and co-workers, and Herrmann & Bohm made independent reports of room-temperature Sonogashira reactions of aryl bromides. The former group employed $Pd(PhCN)_2Cl_2/P(t\text{-}Bu)_3$ catalyst and CuI cocatalyst system to achieve good to excellent yields (63 – 95% isolated yields),[63] and the latter group used copper-free $Pd_2(dba)_3/P(t\text{-}Bu)_3$ catalyst system to obtain moderate to excellent yields (42 – 100% GC yields).[62]

Application of the $Pd(PA\text{-}Ph)_2$-dba system to the Sonogashira reaction proved to be highly successful. In the reactions involving aryl iodides, preliminary screening revealed that coupling could be affect in less than one hour in high yields by using a combination of the 2% $Pd(PA\text{-}Ph)_2$-dba and 2% CuI. Reaction parameter optimization revealed that acetonitrile was the best solvent and diisopropylethylamine the base of choice for most of the substrates. In some instances, Cs_2CO_3 was found to be more effective.

The optimum conditions were applied to an array of aryl iodides and terminal alkyne coupling partners and the results appear in Table 11. The general protocol effected Sonogashira coupling of activated (entry 2), deactivated (entries 3, 5 and 6) and sterically demanding (entry 4) systems at room temperature in roughly one hour in excellent yields.

Table 11. Sonogashira Reaction of Aryl Iodides.

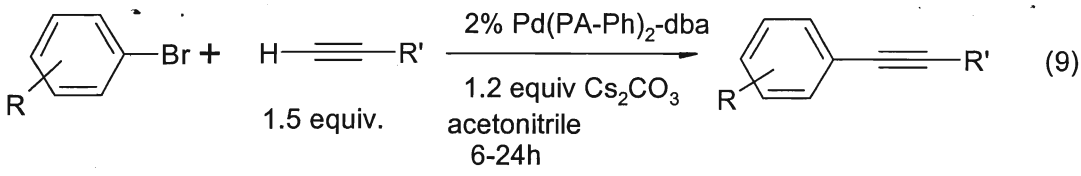


Entry	Aryl Iodide	Alkyne	Product	Yield[a]
1				96%
2				93%
3				91%
4				93%
5[b]				94%
6				92%

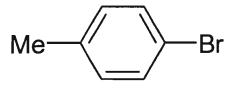
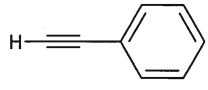
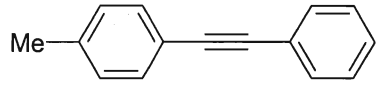
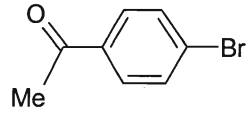
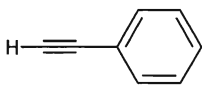
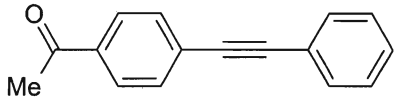
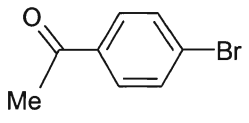
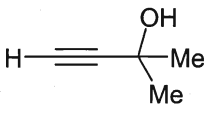
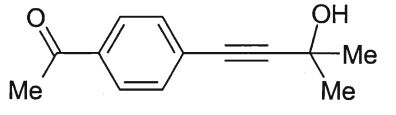
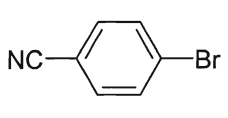
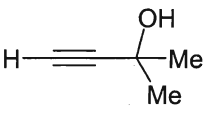
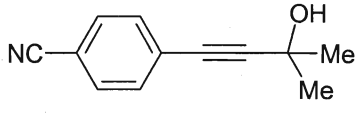
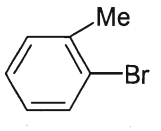
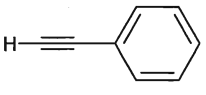
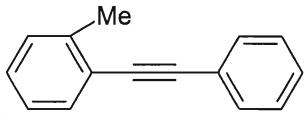
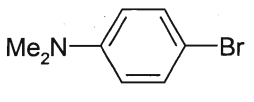
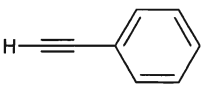
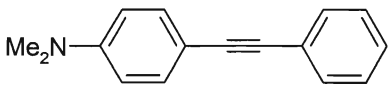
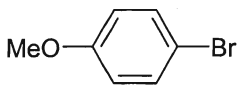
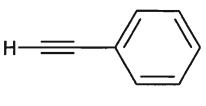
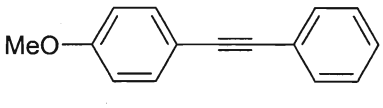
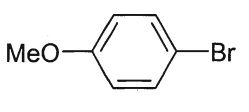
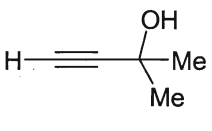
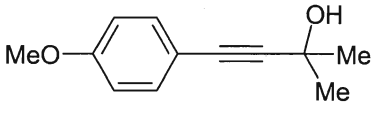
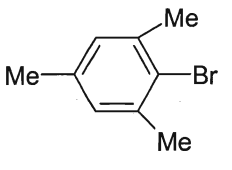
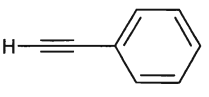
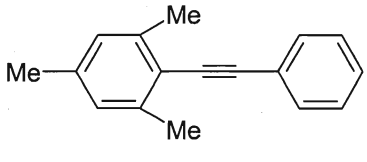
[a]Isolated yield, [b]Cs_2CO_3 was used.

Interestingly, omission of the CuI co-catalyst in the aryl iodide series required an increase in temperature (generally to 50 °C) to achieve the high conversions in short reaction times. For example, in the absence of CuI, the Sonogashira cross-coupling 4-iodoanisole with phenylacetylene afforded only 10% conversion after one hour at room temperature. However, the same reaction proceeded to completion within an hour at 50°C (*c.f.* Table 11, entry 3).

Table 12. Copper-free Sonogashira Cross-Coupling of Aryl Bromides.



(9)

Entry	Aryl Bromide	Alkyne	Product	Yield[a]
1				95%
2[b]				91%
3[b]				90%
4[b]				90%
5				91%
6				93%
7[c]				90%
8[c]				92%
9[c]				93%

[a]Isolated yield, [b]Reaction carried out at room-temperature, [c]Reaction carried out at 60°C.

Sonogashira coupling of aryl bromides could also be effected the Pd(PA-Ph)$_2$-dba complex. However, in this series, addition of the CuI is actually deleterious to the overall reaction. High conversions were achieved within 6-24 h at between 50 to 60°C in the absence of the CuI. Once again, initial screening was followed by reaction parameter optimization. Acetonitrile was found to be the best solvent with toluene, dioxane, and THF being less effective (giving lower conversions, usually less than 90%). Addition of a small amount of water to acetonitrile was also very effective in some cases. But, for example, when 95% ethanol was used as solvent in the cross-coupling of 4-bromotoluene with 2-methyl-3-butyn-2-ol, no reaction occurred after 24 hours at room-temperature; however, over 90% conversion was achieved when the same reaction was repeated in a 2:1 mixture of acetonitrile and water. Optimized results appear in Table 11.

It is not completely understood why the Cu co-catalyst promotes the Sonogashira coupling of aryl iodides while hampering the coupling of aryl bromides. It was found that copper-free reactions of aryl bromides at 50 or 60 °C occur effectively and were completed within 6-20 hours (entries 1-9, Table 12). But reactions involving CuI as co-catalyst were not completed even after 24 hours.For example, whereas 100% conversion was achieved for the reaction of 4-bromoanisole with phenylacetylene at 60 °C, the same reaction, when repeated with 2% CuI gave only 10% conversion. Further mechanistic work is needed to explain this curious phenomenon.

8. Palladium-catalyzed α-arylation of ketones.

The palladium-catalyzed reaction of aryl halides with ketones has emerged as one of the most versatile and direct ways of making α-arylated ketones. A plausible catalytic cycle is shown in Figure 7. Oxidative addition of an aryl halide to a Pd(0) complex forms an arylpalladium(II) halide complex (**18**).

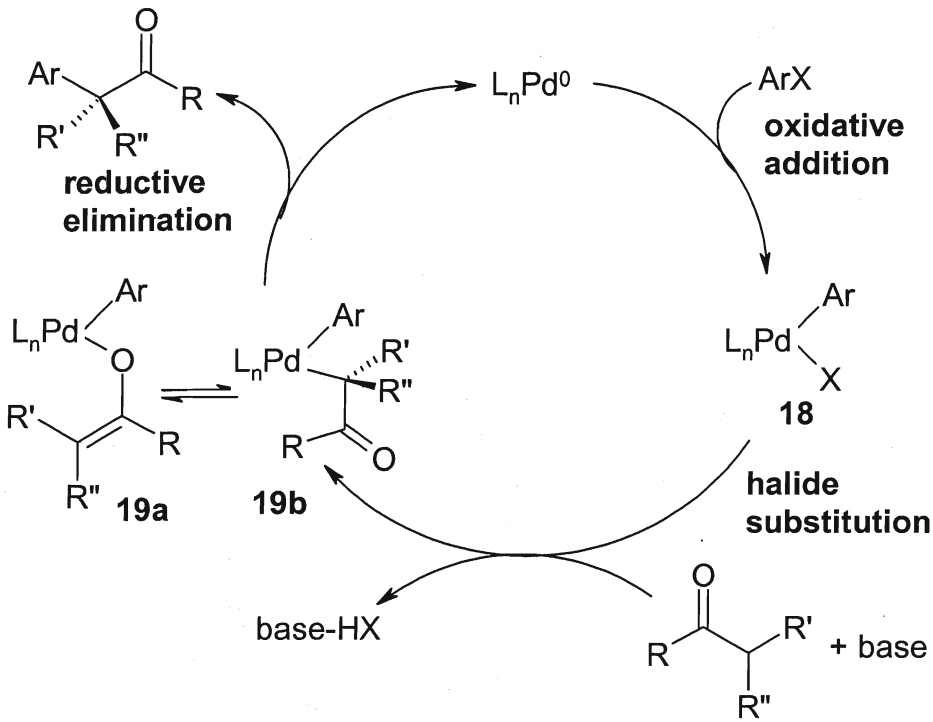
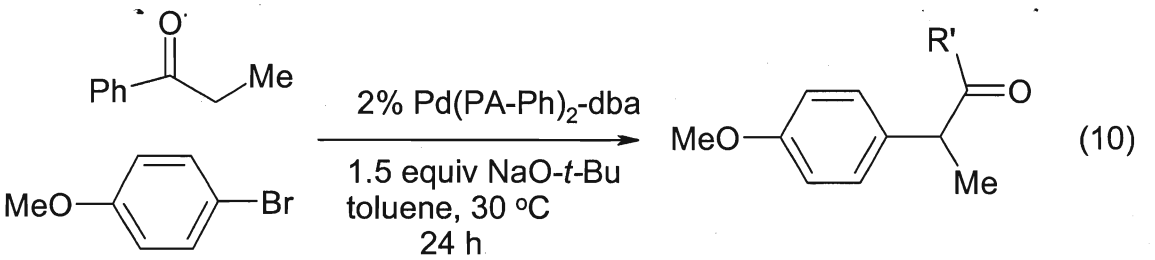


Figure 7. mechanism of ketone arylation.

Substitution of the coordinated halide by an enolate nucleophile and reductive elimination from the resulting palladium enolate complex (**19a** or **19b**) would form the α -aryl ketone and regenerate the Pd(0) complex that started that the cycle.[104]

As discussed in the introduction, the discovery that bulky, electron-rich phosphines act as effective ligands in these reactions has resulted in the establishment of numerous protocols for generating α -aryl ketones. Given the interest in the reaction, we became anxious to apply the $Pd(PA\text{-}Ph)_2$-dba complex to this coupling reaction.

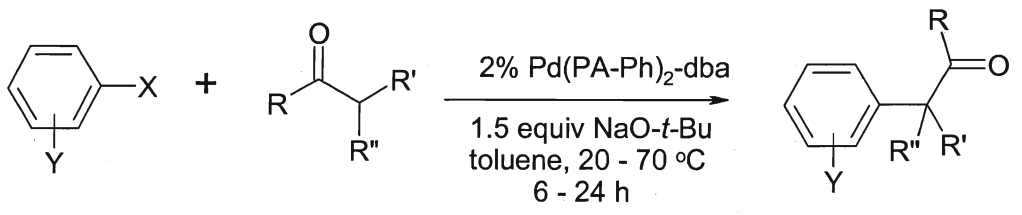


(10)

The reaction of 4-bromoanisole with propiophenone (equation 8) was selected for optimization studies. This reaction was used to screen for solvent, base, catalyst loading at varying temperatures. NaO^{t}Bu was selected for the initial screening based on the fact that NaO^{t}Bu is the base widely used in Pd-catalyzed ketone arylation reactions. KO^{t}Bu was shown to be less effective. While THF is the solvent most commonly used in this type of reaction, in our hands, excellent results were obtained when the reaction was carried out in toluene. In fact, THF or toluene/THF solvent mixtures were much less effective. For example, coupling of 4-bromoanisole with propiophenone in toluene proceeded to total completion at 30 °C after 24 h, whereas the THF reaction did not proceed at 30 °C. Increasing the temperature to 40°C allowed for a 40 % conversion in THF and an 80 % conversion in toluene/THF (2:1). One plausible explanation in the marked difference between THF and toluene is that THF may interact with the coordination site of the intermediate Pd(PA-Ph)$_2$ complex and slows down the rate of oxidative addition.

When Pd(PA-Ph)$_2$O$_2$ was employed as the catalyst for the reaction in equation 10, no product was formed at 30 °C but when this reaction reaction was repeated at 40 °C, 80% conversion was achieved after 24 hours.

Optimum conditions were applied to a variety of coupling partners and the results are presented in Table 13 Overall, the Pd(PA-Ph)$_2$-dba complex provides an effective catalyst system for the *a*-arylation of ketones. In fact, this "all-in-one" ligand-metal complex has demonstrated itself to be one of the most active catalysts reported to date. For example, the Pd(PA-Ph)$_2$-dba catalyzed reaction of 4-bromoanisole (an unactivated system) with propiophenone at 30 °C afforded the coupled product in 99% yield (Table 13 entry 4) in 24 h using NaO^{t}Bu as the base. A survey of the chemical literature has revealed that other well known ligands like P(*t*-Bu)$_3$ and its derivatives effect the same reaction at 50 °C (20 degrees higher!).[68]



(11)

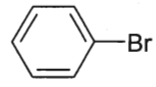
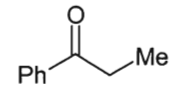
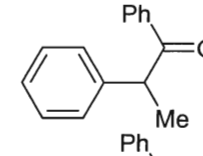
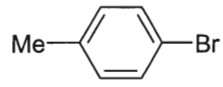
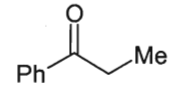
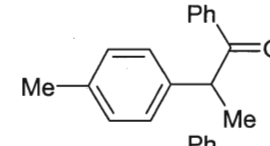
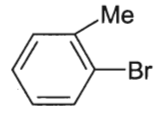
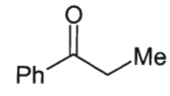
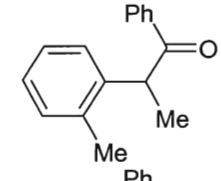
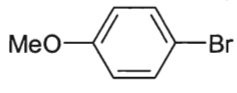
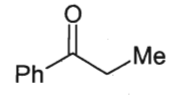
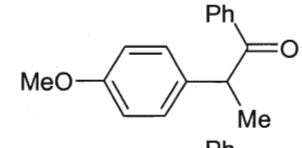
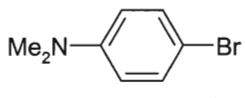
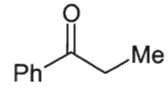
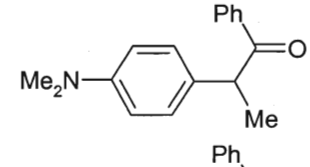
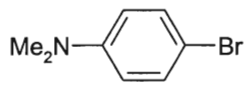
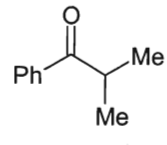
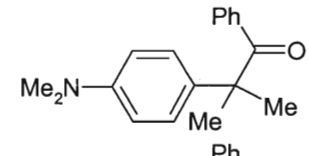
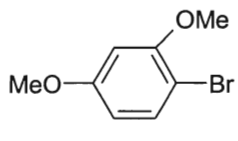
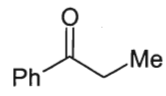
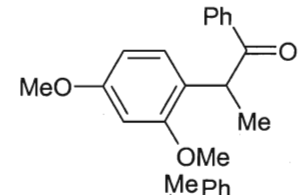
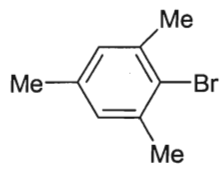
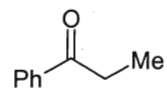
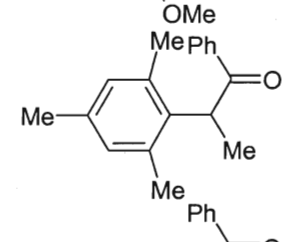
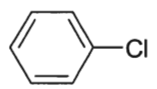
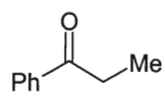
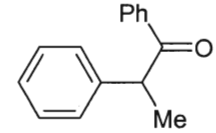
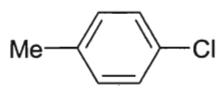
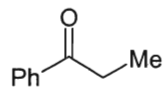
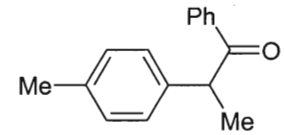
X = Br, Cl
Y = 2-Me, H
4-Me, MeO
NMe_2
2,4-MeO
2,4,6-Me

R = Ph
R = Me
R = Me, H

75 - 99%

As can be seen from Table 13, the reaction of bromobenzene with propiophenone occured at 20 °C to afford excellent yield (entry 1) with a catalyst loading as low as 1 mol %. It is interesting to note that the Pd(PA-Ph)$_2$-dba system provides excellent yields with an array of electron-rich and hindered aryl bromides, as well. For instance, the reaction between the highly deactivated 2,4-dimethoxybromobenzene and propiophenone at 40 °C affords the coupled product in 80 % isolated yield (table 13, entry 7) and the reaction of sterically hindered 2,4,6-mesitylbromide with propiophenone at 40 °C to affords an 87 % yield of the di-*ortho*-substituted α-arylated ketone.

Table 13: $Pd(PA\text{-}Ph)_2$ catalyzed ketone arylation.

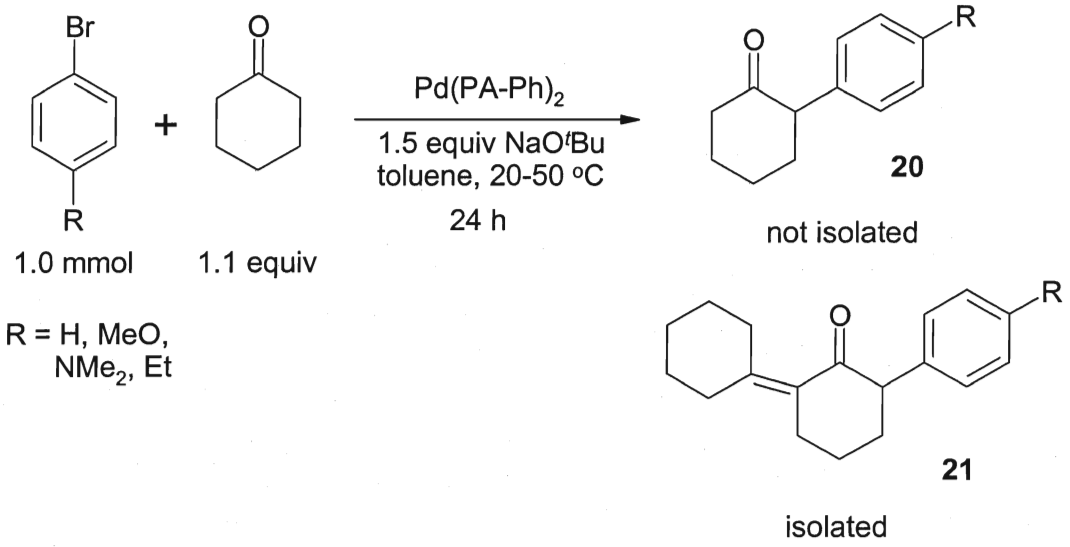
Entry	Aryl Halide	Ketone	Product	Yield[a]
1[b]				93%
2[c]				96%
3[c]				95%
4[c]				99%
5[c]				98%
6[d]				85%
7[d]				80%
8[d]				87%
9[e]				75%
10[e]				78%

[a]Isolated yield. Reaction temperatures: [b]40 °C, [c]30 °C, [d]40 °C, [e]70 °C.

Despite the additional steric crowding about the α-position in isobutyrophenone,

reaction with electron-rich *N,N*-dimethyl-4-bromoaniline afforded an 85 % yield of the coupled product (table 13, entry 6). Finally, Pd(PA-Ph)$_2$-dba catalyzed α-arylation of ketones using aryl chlorides was also achieved. Entries 9 and 10 gave satisfactory results (comparable to those already described in the literature) at 70 °C.

An unusual observation was made when cyclohexanone was employed as the ketone-coupling component. All reactions that were carried out using cyclohexanone



(12)

failed to give the desired product. Various aryl bromides were reacted with cyclohexanone and each time only the arylated/aldol products were isolated even at 20 °C (equation 12).

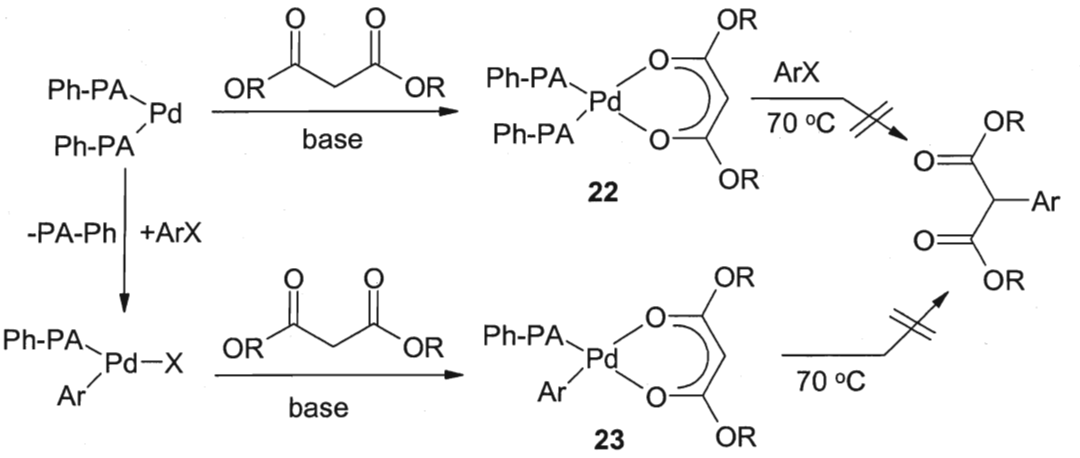
This rather unexpected result raised two questions; could this be due to the reactivity of Pd(PA-Ph)$_2$-dba, or could it be due to the choice of ketone, cyclohexanone? There are many reports in the literature involving the use of cyclohexanone in which the desired product **20** has been isolated in high yield, and no reported cases of isolation of the side product **21**.[65,67,68,70] Monitoring of the reaction over time provided some insight. The reaction between bromobenzene and cyclohexanone was followed by GC/MS

analysis and after 4 h, both **20** and **21** where present in almost equal amounts along with unreacted cyclohexanone. When this reaction was allowed to proceed for an additional 24 h only **21** was isolated. This seems to indicates that the once **20** is formed it reacts with cyclohexanone to give **21**. Unreacted aryl bromide was isolated in all the reactions investigated.

Another curious feature of this catalyst system was the inability of $Pd(PA\text{-}Ph)_2$-dba to catalyze the reaction of an aryl bromide with diethyl malonate. No product was formed at 70 °C although temperatures higher than 70 °C were not tried. One plausible explanation involves the formation of a stable complex between the malonate anion and the $Pd(PA\text{-}Ph)_2$-dba. If this should take place then oxidative addition would be prohibited. It is not clear if the malonate anion reacts with $Pd(PA\text{-}Ph)_2$-dba before oxidative addition or if it reacts with the intermediate arylpalladium(II) halide and prevents oxidative addition. The former is likely to happen if the bisphosphine palladium complex, $Pd(PA\text{-}Ph)_2$ is the active catalyst (equation 13). The latter is highly possible if the notion that the monophosphine palladium complexs is the active species when bulky, electron-rich phosphines are employed as ligands.[77]

Hartwig and Wolkowski have done some excellent work that provides an insight into the reactivity of malonates.[68, 85] In their investigation, they concluded that arylpalladium complexes of malonate ions ligated by certain phosphines were too stable to undergo reductive elimination (equation 13). The authors went on to say that transition metal complexes of enolate, cyanoalkyl, and malonate anions can display several coordination modes; and both the anion and phosphine influenced the connectivity. They

stressed further that complexes containing monophines such as PPh_3, bound the malonate in the η^2-O,O-bound form of **22** and **23,** even in the presence of additional phosphine.



(13)

Unfortunately, further experimentation was not carried out in our case to ascertain the possibility of the formation of a stable arylpalladium η^2-manolate complex **22** or **23** (equation 13).

CONCLUSION

The results from our study show that the phospha-adamantane derivatives act effectively as ligands promoting the Suzuki, Sonogashira and ketone arylation palladium-catalyzed cross-coupling reactions. The Suzuki cross-coupling of aryl halides with arylboronic acids was achieved successfully with high yields, comparable to current results obtained with other ligands such as P(*t*-Bu)$_3$. The air stability and the inherent ability of these ligands to form stable palladium complexes has allowed for the synthesis and application of a new class of palladium bisphosphine complex in the Sonogashira reaction and ketone arylation. The products from these cross-couplings were obtained in high yields at surprisingly mild temperatures.

Clearly, the phospha-adamantane ligands and their palladium complexes showed remarkable advantages over many other phosphines in that they are air stable and easily prepared with relatively cheap starting materials. The parent, secondary phospha-adamantane (**14**), while unsuitable for use as ligand, nonetheless serves as an excellent framework upon which a variety of aryl and alkyl groups can be introduced. This additional functionalization makes the system unique and delivers the promise of great potential.

Future Work:

Many other researchers have described the use of different types of bulky, electron-rich phosphine ligands in palladium-catalyzed cross-couplings. The tertiary phospha-adamantanes provide a number of advantages (air stable, easy-to-handle and highly active), however, that the other systems do not. Furthermore, the additional

functionality that can be installed allows for a plethora of other derivatives to be prepared; each with slightly different steric and electronic properties. The synthesis of a library of tertiary phospha-adamantane ligands and their application in other types of cross-couplings are currently under investigation in our laboratory. The Capretta group is now identifiying new applications for these ligands such as Heck, Stille, and Negishi reactions. Others in our laboratory are finding application of these ligands together with newly discovered ones in Amination, Heck, and Alkyl-Alkyl cross-couplings. Additional work should be directed towards the development of the stable palladium complexes of the phospha-adamantanes and their ability to act as active "all-in-one" catalyst systems in cross-coupling reactions. Clearly, the results obtained in the Sonogashira and ketone arylation reactions with $Pd(PA\text{-}Ph)_2$-dba demonstrated that it can be used as a suitable catalyst in many cross-coupling reactions and this needs to explored. Other phospha-adamantane ligands like PA-o-tolyl also form air stable palladium complexes and investigation into their catalytic activity should be given attention.

EXPERIMENTAL

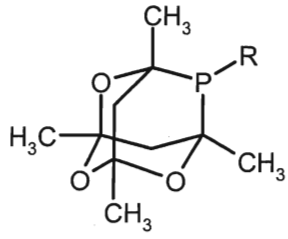
APPARATUS AND MATERIALS

Proton magnetic resonance (^{1}H NMR) spectra were recorded on a Bruker Avance DPX-300 Digital FT spectrometer (at 300.13 MHz) with chloroform-d as the solvent unless otherwise noted. Unless specified, the usual internal reference was tetramethylsilane (TMS). The abbreviations (s) = singlet, (d) = doublet, (t) = triplet, (q) = quartet, and (m) = multiplet are used in the description of the spin-spin splitting pattern present in the spectra.

The natural abundance carbon-13 magnetic resonance (^{13}C NMR) was recorded on a Bruker Avance DPX-300 Digital FT spectrometer (at 75.03 MHz) using chloroform-d as the solvent and internal reference unless noted. All ^{13}C NMR spectra were broad band decoupled.

Low resolution mass spectra (MS) and high resolution mass spectra (HRMS) were obtained on Carlo Erba/Kratos HRGS/MS Concept 1S double focusing mass spectrometer interfaced to a Kratos DART acquisition system and a SUN SPARC workstation. Samples were introduced through a direct inlet. Ions were generated using electron impact (EI) or fast atomic bombardment (FAB).

Gas chromatography (GC) analyses were carried out on HP 5890 equipped with MS HP 5970 MSD series.



PA-R

14. R = H (**PA-H**)
15. R = Ph (**PA-Ph**)
16. R = 2-tolyl (**PA-o-toluoyl**)
17. R = $C_{14}H_{29}$ (**PA-$C_{14}H_{29}$**)

Figure 1

Ligands **14**, **15, 16** and **17** (Cytec Canada Inc), $Pd_2(dba)_3$ (Aldrich), $Pd(OAc)_2$ and (Aldrich) P(*t*-Bu)$_3$ (Strem) were used as received. $Pd_2(dba)_3.CHCl_3$ was prepared according to literature procedure.[3]

o-Tolylboronic acid (Aldrich), phenylboronic acid Aldrich), 4-methoxyphenylboronic acid (Aldrich), and 4-acetylphenylboronic acid (Aldrich), were recrystallized from water prior to use. All aryl iodides, aryl bromides and aryl chlorides, phenylacetylene and 2-methyl-3-butyn-2-ol were purchased from Aldrich and were used as received.

K_3PO_4 (Aldrich) and Cs_2CO_3 (Fluka) were ground to a fine powder using a mortar and a pestle and dried in a vacuum oven prior to use. KF (Aldrich, spray dried) was dried in a vacuum oven overnight. Et_3N and (*i*-Pr)$_2$NEt were distilled prior to use. THF and dioxane were distilled under argon from sodium/benzophenone. Toluene was distilled under argon from molten sodium and acetonitrile was degassed prior to use.

SYNTHETIC PROTOCOLS

General Procedure for Suzuki Cross-Coupling Reactions

All Suzuki cross-coupling reactions were assembled under an argon atmosphere either in oven dried septum-cap vial or in a resealable Schlenk tube. Because the yields

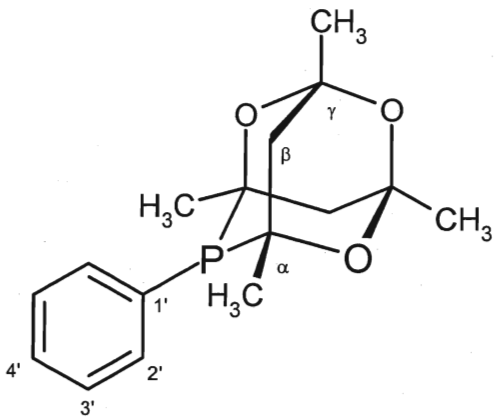
that are reported in the Tables are the average of two runs, the yields that are reported below for the specific experiments may differ from the values presented in the tables slightly.

Procedure A. The arylboronic acid, K_3PO_4, the palladium source, the ligand and aryl halide (if a solid), are added to an oven dried 10-mL reaction tube equipped with a stir bar and kept under high vac for 5- 10 minutes. Argon inlet and outlet are attached and the reaction mixture is bubbled with argon. Freshly distilled toluene is added by syringe and the reaction mixture is stirred at room temperature under argon for the indicated time. At the conclusion of the reaction, the reaction mixture is loaded unto a 10 cm silica gel column and washed with copious amounts of Et_2O or EtOAc, concentrated and purified by column chromatography on silica gel.

Procedure B. The arylboronic acid, K_3PO_4, and the palladium source are added to an oven dried 10-mL reaction tube equipped with a stir bar. The tube is capped with a septum and kept under high vac for 5- 10 minutes and then filled with argon. A solution of the ligand (0.20 M solution in toluene under argon) is added followed by the aryl halide (if a liquid) and toluene. The reaction mixture is further bubbled with argon and stirred at room temperature for the indicated time. At the conclusion of the reaction, the reaction mixture is loaded unto a 10 cm silica gel column and washed with copious amounts of Et_2O or EtOAc, concentrated and purified by column chromatography on silica gel.

Procedure C. The arylboronic acid, K_3PO_4 or Cs_2CO_3, the palladium source, the ligand, are added to an oven dried Schlenk tube. The Schlenk tube was capped with a rubber septum, high vac, filled with argon, evacuated and backfilled with argon. The aryl halide and toluene are added and three freeze-pump-thaw cycles are then performed. The reaction is stirred at the indicated temperature and time. At the conclusion of the reaction, the reaction mixture is loaded unto a 10 cm silica gel column and washed with copious amounts of Et_2O or EtOAc, concentrated and purified by column chromatography on silica gel.

1,3,5,7-tetramethyl-6-phenyl-2,4,8-trioxa-6-phosphaadamantane (15)



^{1}H NMR: ($CDCl_3$, 300 MHz):δ 1.25 (3H, d, $^3J_{P\text{-}H}$ 12.9, α-Me), 1.38 (6H, s, 2 γ-Me), 1.48 (1H, dd, J_{gem} 13.4 & $^3J_{P\text{-}H}$ 4.1, 0.5 CH_2), 1.52 (3H, d, $^3J_{P\text{-}H}$ 12.7, α-Me), 1.78 (1H, d, J_{gem} 13.4, 0.5 CH_2), 1.93 (1H, dd, $^3J_{P\text{-}H}$ 24.3 & J_{gem} 13.1, 0.5 CH_2), 2.07 (1H, d, J_{gem} 13.1 & $^3J_{P\text{-}H}$ 7.0, 0.5 CH_2), 7.36-7.38 (3H, m, H-Ar), 7.80-7.85 (2H, m, H-Ar).

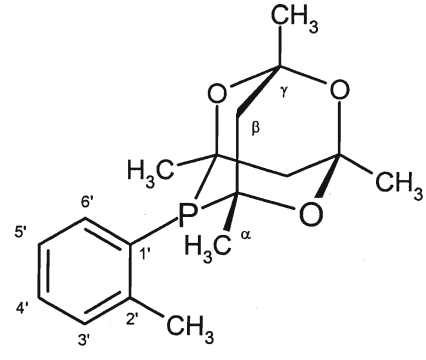
^{13}C NMR: ($CDCl_3$, 75 MHz): δ 26.8 (d, $^2J_{P\text{-}C}$ 11.5, α-Me), 27.4 (d, $^2J_{P\text{-}C}$ 22.1, α-Me), 27.8, 28.0 (s, γ-Me), 36.2 (d, $^2J_{P\text{-}C}$ 1.6, CH_2), 45.4 (d, $^2J_{P\text{-}C}$ 17.4, CH_2), 73.1 (d, $^1J_{P\text{-}C}$ 7.6, α-q), 73.4 (d, $^2J_{P\text{-}C}$ 21.8, α-q), 96.0, 96.8 (s, γ-q), 128.3 (d, $^3J_{P\text{-}C}$ 7.2, C-3'), 129.4 (s, C-4'), 133.9 (d, $^1J_{P\text{-}C}$ 26.9, 1'-q), 135.0 (d, $^2J_{P\text{-}C}$ 19.7, C-2').

^{31}P NMR: (81 MHz, $CDCl_3$): δ –23.6.

MS[EI+]: *m/z* (RI%): 292 (M^+, 16%), 192 (100), 177 (38), 43 (71).

HRMS (CI, M+H): found for $C_{16}H_{22}O_3P$, 293.1314; calculated 293.1307.

1,3,5,7-tetramethyl-6-o-tolyl-2,4,8-trioxa-6-phosphaadamantane (16).



^{1}H NMR: ($CDCl_3$, 300 MHz): δ 1.28 (3H, d, $^3J_{P\text{-}H}$ 12.2, α-Me), 1.43, 1.44 (3H, s, γ-Me), 1.47 (3H, d, $^3J_{P\text{-}H}$ 12.9, α-Me), 1.95 (1H, d, J_{gem} 13.4, 0.5 CH_2), 1.96 (1H, dd, $^3J_{P\text{-}H}$ 25.1 & J_{gem} 13.4, 0.5 CH_2), 2.11 (1H, dd, J_{gem} 13.4 & $^3J_{P\text{-}H}$ 7.5, 0.5 CH_2), 2.61 (3H, s, PhMe), 7.18-7.27 (3H, m, H-Ar), 8.15-8.18 (1H, m, H-Ar).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 22.0 (d, $^2J_{P\text{-}C}$ 25.4, α-Me), 26.6 (d, $^2J_{P\text{-}C}$ 11.3, α-Me), 27.8, (s, γ-Me), 27.9 (d, $^3J_{P\text{-}C}$ 19.9, 2'-Me), 28.0 (s, γ-Me), 36.0 (s, CH_2),

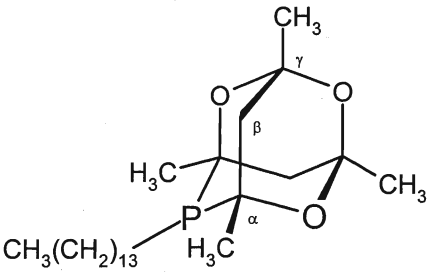
46.0 (d, $^{2}J_{P\text{-}C}$ 18.9, CH_2), 73.4 (d, $^{1}J_{P\text{-}C}$ 23.2, α-q), 74.1 (d, $^{1}J_{P\text{-}C}$ 8.0, α-q), 96.0, 96.8 (s, γ-q), 125.8, 129.3 (s, Ar-CH), 130.6 (d, $J_{P\text{-}C}$ 5.3, Ar-CH), 132.2 (d, $^{1}J_{P\text{-}C}$ 28.4, 1'-q), 133.3 (d, $J_{P\text{-}C}$ 3.1, Ar-CH), 145.2 (d, $^{2}J_{P\text{-}C}$ 28.1, 2'-q).

^{31}P NMR: ($CDCl_3$ 81 MHz): δ –38.5.

MS[EI+]: *m/z* (RI%): 306 (M^+, 31%), 206 (100), 191 (45), 43 (94).

HRMS: for $C_{17}H_{23}O_3P$: found for $C_{17}H_{24}O_3P$, 307.1478; calculated 307.1463.

1,3,5,7-tetramethyl-6-tetradecyl-2,4,8-trioxa-6-phosphaadamantane (17).



^{1}H NMR: ($CDCl_3$, 300 MHz): δ 0.88 (3H, t, *J* 6.5, Me), 0.95-1.05 (2H, m, CH_2), 1.26 (20H, s, CH_2), 1.29 (3H, d, $^{3}J_{P\text{-}H}$ 2.8, α-Me), 1.33 (3H, d, $^{3}J_{P\text{-}H}$ 3.6, α-Me), 1.36 (6H, s, γ-Me), 1.49 (2H, t, *J* 7.5, CH_2), 1.56 (1H, dd, J_{gem} 13.3 and $^{3}J_{P\text{-}H}$ 4.1, 0.5 CH_2), 1.57 (1H, d, J_{gem} 13.3, CH_2), 1.78 (1H, dd, $^{3}J_{P\text{-}H}$ 21.4 & J_{gem} 12.9, CH_2), 1.95 (1H, dd, J_{gem} 12.9 & $^{3}J_{P\text{-}H}$ 6.5, 0.5 CH_2).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 14.1 (s, Me), 21.1 (d, $J_{P\text{-}C}$ 21.9, CH_2), 22.7 (s, CH_2), 26.8 (d, $^{2}J_{P\text{-}C}$ 12.7, α-Me), 27.8, 28.0 (s, γ-Me), 28.0 (d, $^{2}J_{P\text{-}C}$ 22.2, α-Me), 28.3 (d, $J_{P\text{-}C}$ 21.7, CH_2), 29.3, 29.4, 29.5, 29.6, 29.7 (CH_2), 31.4 (d, $J_{P\text{-}C}$

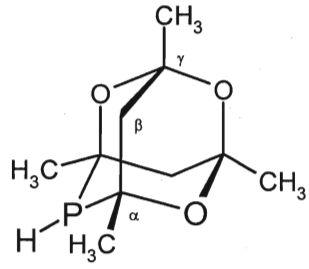
12.5, CH_2), 31.9 (s, CH_2), 31.9 (s, ring-CH_2), 44.5 (d, $^2J_{P\text{-}C}$ 15.0, ring-CH_2), 71.9, 72.2 (s, α-q), 95.7, 96.6 (s, γ-q).

^{31}P NMR: ($CDCl_3$, 81 MHz): δ -28.0.

MS[EI+]: *m/z* (RI%): 412 (M^+, 5%), 312 (56), 269 (18), 130 (44), 115 (100), 43 (97).

HRMS: found for $C_{24}H_{45}O_3P$, 412.3118; calculated 412.3106.

1,3,5,7-tetramethyl-2,4,8-trioxa-6-phosphaadamantane (14).



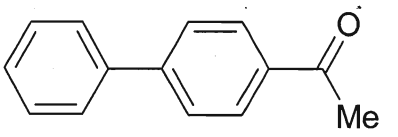
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 1.38, 1.39 (3H, s, γ-Me), 1.44, 1.49 (3H, d, $^3J_{P\text{-}H}$ 5.6, α-Me), 1.73 (1H, d, J_{gem} 12.8, 0.5 CH_2), 1.77-1.83 (3H, m, 1.5 CH_2), 1.92 (1H, dd, J_{gem} 12.8 & $^3J_{P\text{-}H}$ 2.6, 0.5 CH_2), 3.08 (1H, dd, $^1J_{P\text{-}H}$ 191.8 & ^4J 1.9, H-P).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 27.8, 29.0 (s, γ-Me), 29.5 (d, $^2J_{P\text{-}C}$ 13.3, α-Me), 30.2 (d, $^2J_{P\text{-}C}$ 22.7, α-Me), 42.7 (d, $^2J_{P\text{-}C}$ 14.5, CH_2), 45.2 (d, $^2J_{P\text{-}C}$ 4.8, CH_2), 70.3 (d, $^1J_{P\text{-}C}$ 3.5, α-q), 72.0 (d, $^1J_{P\text{-}C}$ 18.4, α-q), 96.4, 96.7 (s, γ-q).

^{31}P NMR ($CDCl_3$: 81 MHz): δ -49.2.

MS[EI]: *m/z* (RI%): 216 (M^+, 15%), 116 (30), 101 (32), 69 (24), 43 (100).

HRMS: found for $C_{10}H_{17}O_3P$, 216.0936; calculated 216.0915.



Synthesis of 4-Acetylbiphenyl (Table 1, entry 1).

Procedure A was followed, with 4'-iodoacetophenone (246 mg, 1.00 mmol), phenylboronic acid (182 mg, 1.50 mmol), K_3PO_4 (637 mg, 3 mmol), $Pd_2(dba)_3.CHCl_3$ (31 mg, 0.030 mmol), PA-Ph (ligand **15** 17.5 mg, 0.060 mmol), and toluene (2 mL). After 2 hours at room temperature, work up and column chromatography (20% Et_2O in hexane) yielded 194 mg (98%) of the title compound as a light yellow solid.

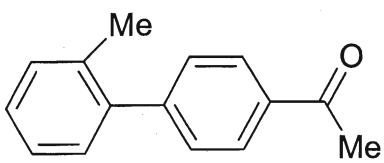
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 8.10 (d, 2H, J = 8.3 Hz), 7.73 (d, J = 8.2 Hz, 2H), 7.68 (d, J = 7.1 Hz, 2H), 7.43-7.52 (m, 3H), 2.69 (s, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 198.2, 146.2, 140.3, 136.2, 129.3, 129.3, 128.6, 127.7, 127.6, 27.1.

MS[EI+]: *m/z* (RI %.) 196 (61), 181 (100), 152 (37).

HRMS: for $C_{14}H_{12}O$: calculated 196.08881, observed 196.08875

Synthesis of 4-Acetyl-2'-methylbiphenyl (Table 1, entry 2).



Procedure A was followed, with 4'-iodoacetophenone (123 mg, 0.500 mmol), o-tolylboronic acid (102 mg, 0.75 mmol), K_3PO_4 (255 mg, 1.2 mmol), $Pd_2(dba)_3.CHCl_3$ (5.2 mg, 0.0050 mmol), PA-Ph, ligand **15** (3 mg, 0.01 mmol), and toluene (1 mL). After 3 hours at room temperature, work up and column

chromatography (10% Et_2O in hexane) yielded 197 mg (94%) of the title compound as a light yellow liquid.

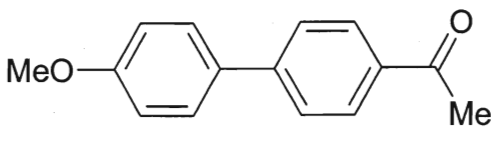
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 8.05 (d, J = 8.2 Hz, 2H), 7.45 (d, J = 8.2 Hz, 2H), 7.26-7.32 (m, 4H), 2.67 (s, 3H), 2.31 (s, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 197.8, 147.0, 140.8, 135.6, 135.2, 130.6, 129.6, 129.5, 128.3, 128.0, 126.0, 26.7, 20.4.

MS[EI+]: *m/z* (RI %): 210 (53.5), 195 (100), 165 (22.4), 152 (15.6).

HRMS: for $C_{15}H_{14}O$: calculated 210.10446, observed 210.10499.

Synthesis of 4-Acetyl-2'-methylbiphenyl (Table 1, entry 3).



Procedure B was followed, using 4'-iodoacetophenone (246 mg, 1.00 mmol), 4-methoxyphenylboronic acid (183 mg, 1.2 mmol), K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.010 mmol), PA-Ph, ligand **15** (0.02 M toluene solution; 0.100 mL , 0.0200 mmol), and toluene (2 mL). After 7 hours at room temperature, work up and column chromatography (50% Et_2O in hexane) yielded 217 mg (96%) of the title compound as a white solid.

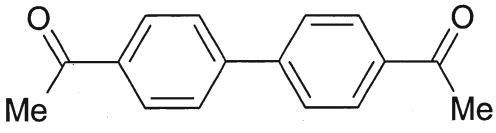
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 8.02 (d, J = 8.3 Hz, 2H), 7.66 (d, J = 8.4 Hz, 2H), 7.60 (d, J = 8.6 Hz, 2H), 7.02 (d, J = 8.7 Hz, 2H), 3.88 (s, 3H), 2.65 (s, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 198.1, 160.3, 145.8, 135.7, 132.6, 129.3, 128.8, 127.0, 114.8, 55.8, 27.0.

MS[EI+]: *m/z* (RI%.): 226 (79.5), 211 (100), 139 (20.3).

HRMS: for $C_{15}H_{14}O_2$: calculated 226.09938, observed 226.09903.

Synthesis of 4,4'-Diacetylbiphenyl (Table 1, entry 4).



Procedure B was followed, using 4'-iodoacetophenone (246 mg, 1.00 mmol), 4-acetylphenylboronic acid (246 mg, 1.5 mmol), K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.010 mmol), PA-Ph, ligand **15** (0.02 M toluene solution; 0.150 mL , 0.0300 mmol), and toluene (2 mL), THF (0.200 mL) and water (0.200 mL). At the conclusion of the reaction at 40 °C, work up and column chromatography (50% Et_2O in hexane) yielded 225 mg (94%) of the title compound as a white solid.

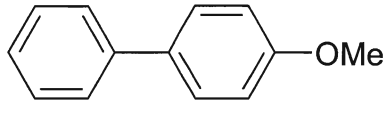
^1H NMR: ($CDCl_3$, 300 MHz): δ 8.10 (d, J = 8.4 Hz, 2H), 7.74 (d, J = 8.3 Hz, 2H), 2.67 (s, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ198.0, 144.7, 136.9, 129.4, 127.8, 27.1.

MS[EI+]: *m/z* (RI%.): 238 (43.6), 223 (100), 152 (16.5).

HRMS: for $C_{16}H_{14}O_2$: calculated 238.09938, observed 238.09962.

Synthesis of 4-Methoxybiphenyl (Table 2, entry 1).



Procedure A was followed, using 4-iodoanisole (234 mg, 1.00 mmol), phenylboronic acid (183 mg, 1.500 mmol), K_3PO_4 (637 mg, 3 mmol), $Pd_2(dba)_3.CHCl_3$ (31 mg, 0.030 mmol), PA-Ph, ligand **15** (0.02 M toluene solution; 0.300 mL , 0.0600 mmol), and toluene (2 mL). After 5 hours at room temperature, work up and column

chromatography (10% Et_2O in hexane) yielded 180 mg (98%) of the title compound as a pale yellow solid.

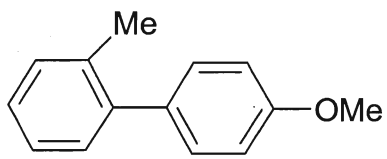
^1H NMR: ($CDCl_3$, 300 MHz): δ 7.54-7.60 (m, 4H), 7.42-7.47 (m, 2H), 7.28-7.36 (m, 1H), 7.00-7.03 (m, 2H), 3.88 (s, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 55.7, 114.6, 127.06, 127.14, 127.6, 128.6, 129.1, 134.2, 141.2, 159.5.

MS[EI+]: *m/z* (% rel.): 185 (15.6), 184 (100), 169 (25.9), 141 (25.1), 115 (21.1).

HRMS: for $C_{13}H_{12}O$: calculated 184.08881, observed 184.08918.

Synthesis of 4-Methoxy-2'-methylbiphenyl (Table 2, entry 2).



Procedure B was followed, using 4-iodoanisole (117 mg, 0.500 mmol), o-tolylboronic acid (102 mg, 0.7505mmol), K_3PO_4 (255 mg, 1.2 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.010 mmol), PA-Ph, ligand **15** (0.02 M toluene solution; 0.0750 mL, 0.0150 mmol), and toluene (2 mL). After 4 hours at room temperature, work up and column chromatography (10% Et_2O in hexane) yielded 89 mg (90%) of the title compound as a light yellow liquid.

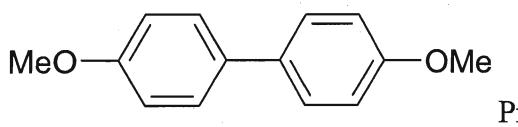
^1H NMR ($CDCl_3$, 300 MHz): δ 7.39-7.34 (m, 6H), 7.06 (d, J = 8.4 Hz, 2H), 3.95 (s, 3H), 2.40 (s, 3H).

^{13}C NMR ($CDCl_3$, 75 MHz): δ 158.6, 141.6, 135.5, 134.4, 130.3, 1130.0, 127.0, 125.8, 113.5, 55.3, 20.6.

MS[EI+]: *m/z* (RI%): 198 (100), 183 (12.5).

HRMS: for $C_{14}H_{14}O$: calculated 198.10446, observed 198.10430.

Synthesis of 4,4'-Dimethoxybiphenyl (Table 2, entry 3).



Procedure B was followed, using 4-iodoanisole (246 mg, 1.0 mmol), 4-methoxyphenylboronic acid (183 mg, 1.20 mmol), K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.010 mmol), PA-Ph, ligand **15** (0.02 M toluene solution; 0.100 mL, 0.020 mmol), and toluene (2 mL). After 6 hours at room temperature, work up and column chromatography (20% EtOAc in hexane) yielded 208 mg (97%) of the title compound as a white solid.

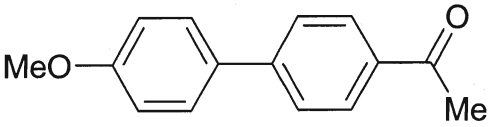
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.50 (d, 4H, J = 8.6 Hz), 6.98 (d, 4H, J = 8.7 Hz), 3.87 (s, 6H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 159.1, 133.9, 128.1, 114.5, 55.7.

MS[EI+]: *m/z* RI%): 215 (15.5), 214 (100), 199 (52.7).

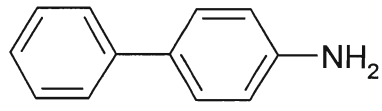
HRMS: for $C_{14}H_{14}O_2$: calculated 214.09938, observed 214.09966.

Synthesis of 4-Acetyl-4'-methoxybiphenyl (Table 2, entry 4).



Procedure B was followed, with 4'-iodoanisole (234 mg, 1.0 mmol), 4-acetylphenylboronic acid (180 mg, 1.1 mmol), K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (0.02 M toluene solution; 0.100 mL, 0.020 mmol), and toluene (2 mL), THF (0.500 mL) and

water (0.100 mL). After 12 hours at room temperature, work up and column chromatography (20% EtOAc in hexane) yielded 213 mg (94%) of the title compound as a white shinning solid. Spectral data were the same as listed above for Table 1, entry 3.



Synthesis of 4-Aminobiphenyl (Table 3, entry 1).

Procedure A was followed, using 4-iodoaniline (219 mg, 1.0 mmol), phenylboronic acid (183 mg, 1.50 mmol), K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.010 mmol), PA-Ph, ligand **15** (8.8 mg, 0.030 mmol), and toluene (2 mL) and THF (0.500 mL). At the conclusion of the reaction at room temperature, work up and column chromatography (10% EtOAc in hexane) yielded 162 mg (96%) of the title compound as a light yellow solid.

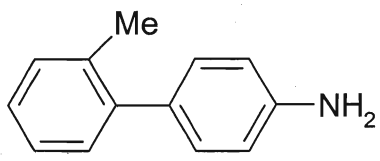
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.64-7.62 (m, 2H), 7.52-7.46 (m, 4H), 7.38-7.33 (m, 1H), 6.81 (d, J = 8.2 Hz, 2H), 3.75 (s, broad, 2H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 146.3, 141.6, 131.4, 129.1, 128.4, 126.8, 126.7, 115.8.

MS[EI+]: *m/z* (RI+%): 169 (100), 168 (16), 167 (18).

HRMS: for $C_{12}H_{11}N$: calculated 169.08915, observed 169.08929.

Synthesis of 4-Amino-2'-methylbiphenyl (Table 3, entry 2).



Procedure A was followed, using 4'-iodoaniline (109.5

mg, 0.50 mmol), o-tolylboronic acid (102 mg, 0.75 mmol), K_3PO_4 (255 mg, 1.2 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, .010 mmol), PA-Ph, ligand **15** (4.4 mg, 0.015 mmol), and toluene (1.5 mL). After 4.5 hours at room temperature, workup and column chromatography (50% Et_2O in hexane) yielded 88 mg (96%) of the title compound as a light yellow liquid.

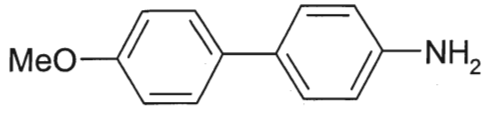
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.29 (m, 4H), 7.04 (d, J = 8.4 Hz, 2H), 7.77 (d, J = 8.3 Hz, 2H), 3.54 (s, broad, 2H), 2.34 (s, 3H).

^{13}C NMR ($CDCl_3$, 75 MHz): δ 145.5, 142.3, 135.9, 132.7, 130.7, 130.5, 130.3, 127.1, 126.1, 115.1, 21.0.

MS[EI+]: *m/z* (RI%): 183 (100), 182 (44), 165 (18).

HRMS: for $C_{13}H_{13}N$: calculated 183.10479, observed 183.10473.

Synthesis of 4-Amino-4'-methoxybiphenyl (Table 3, entry 3).



Procedure B was followed, with 4'-iodoaniline (219 mg, 1.0 mmol), 4-methoxyphenylboronic acid (183 mg, 1.20 mmol), K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, .010 mmol), PA-Ph, ligand **15** (0.02 M toluene solution; 0.100 mL, 0.020 mmol), and toluene (1.5 mL). After 6 hours at room temperature, workup and column chromatography (20% EtOAc in hexane) yielded 187 mg (94%) of the title compound as a light yellow solid.

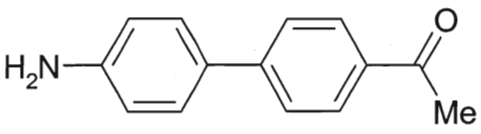
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.38 (d, J = 8.7 Hz , 2H), 7.28 (d, J = 8.2 Hz , 2H), 6.85 (d, J = 8.6 Hz , 2H), 6.66 (d, J = 8.2 Hz , 2H), 3.75 (s, 3H), 3.60 (s, broad, 2H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 158.5, 145.4, 133.9, 131.4, 127.7, 127.5, 115.5, 114.2, 55.4.

MS[EI+]: *m/z* (RI+%): 200 (15), 199 (100), 184 (56), 156 (14).

HRMS: for $C_{13}H_{13}NO$: calculated 199.09971, observed 199.09995.

Synthesis of 4-Acetyl-4'-aminobiphenyl (Table 3, entry 4).



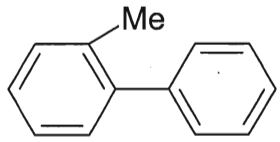
Procedure B was followed, with 4'-iodoaniline (219 mg, 1.0 mmol), 4-acetylphenylboronic acid (246 mg, 1.50 mmol), K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, .010 mmol), PA-Ph, ligand **15** (0.02 M toluene solution; 0.100 mL, 0.020 mmol), and toluene (2 mL), THF (0.500 mL) and water (0.500 mL). At the conclusion of the reaction at room temperature, workup and column chromatography (30% EtOAc in hexane) yielded 194 mg (92%) of the title compound as a light yellow solid.

^{1}H NMR: ($CDCl_3$, 300 MHz): δ 8.01 (d, J = 8.0 Hz, 2H), 7.65 (d, J = 8.0 Hz, 2H), 7.50 (d, J = 8.0 Hz, 2H), 6.80 (d, J = 8.1 Hz, 2H), 2.64 (s, 3H), 1.54 (s, broad, 2H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 198.2, 147.2, 146.1, 135.2, 130.2, 129.4, 128.6, 126.5, 115.7, 27.0.

MS[EI+]: *m/z* (RI+%): 211 (100), 196 (69.6), 167 (41.1).

HRMS: for $C_{14}H_{13}NO$: calculated 211.09971, observed 211.09984.



Synthesis of 2-Methylbiphenyl (Table 4, entry 1).

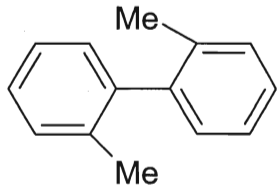
Procedure A was followed, 2-iodotoluene (218 mg, 1.0 mmol), phenylboronic acid (146 mg, 1.2 mmol), K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (6 mg, 0.0200 mmol), and toluene (2 mL). After 1 hour at room temperature, work up and column chromatography (hexane) yielded 164 mg (97%) of the title compound as a pale yellow liquid.

^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.5-7.48 (m, 2H), 7.44-7.41, (m, 3H), 7.37-7.34 (m, 4H), 2.38 (s, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 142.1, 135.4, 130.4, 129.9, 129.4, 129.3, 129.2, 129.2, 128.9, 128.2, 128.2, 127.4, 126.9, 125.9, 20.6.

MS[EI+]: *m/z* (RI%): 168 (100), 167 (76), 153 (17).

HRMS: for $C_{13}H_{12}$: calculated 168.09390, observed 168.09435.



Synthesis of 2,2'-Dimethylbiphenyl (Table 4, entry 2).

Procedure A was followed, 2-iodotoluene (218 mg, 1.0 mmol), o-tolylboronic acid (163 mg, 1.2 mmol) K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (5.8 mg, 0.0200 mmol), and toluene (2 mL). After 2.5 hours at room temperature, work up and column chromatography (hexane) yielded 178 mg (98%) of the title compound as a colorless liquid.

^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.34-7.26 (m, 6H), 7.20 (m, 2H), 2.13 (s, 6H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 142.0, 136.2, 130.2, 129.7, 127.6, 126.0, 20.3.

MS[EI+]: *m/z* (RI%): 182 (100), 167 (89), 165 (45), 115 (7).

HRMS: for $C_{14}H_{14}$: calculated 182.10955, observed 182.10977.

Synthesis of 4-Methoxy-2'-methylbiphenyl (Table 4, entry 3).

Procedure A was followed, 2-iodotoluene (218 mg, 1.0 mmol), 4-methoxyphenylboronic acid (183 mg, 1.2 mmol) K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (5.8 mg, 0.0200 mmol), and toluene (2 mL). At end of the reaction at room temperature, work up and column chromatography (10% Et_2O in hexane) yielded 184 mg (93%) of the title compound as a pale yellow liquid. Spectral data were the same as listed above for Tabel 1, entry 2.

Synthesis of 4-Acetyl-2'-methylbiphenyl (Table 4, entry 4).

Procedure A was followed, 2-iodotoluene (218 mg, 1.0 mmol), 4-acetylphenylboronic acid (246 mg, 1.5 mmol), K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (6 mg, 0.0200 mmol), and toluene (2 mL), THF (0.500 mL) and water (0.200 mL). After 6 hours at room temperature, work up and column chromatography (10% EtOAc in hexane) yielded 202 mg (96%) of the title compound as a light yellow liquid. Spectral data were the same as listed above for Table 1, entry 2.

Synthesis of 4-Acetylbiphenyl (Table 5, entry 1).

Procedure B was followed, with 4'-bromoacetophenone (199 mg, 1.0 mmol), phenylboronic acid (146 mg, 1.2 mmol), K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (0.02 M toluene solution; 0.100 mL, 0.020 mmol), and toluene (2 mL). After 3 hours at room temperature, work up and column chromatography (10% Et_2O in hexane) yielded 194 mg (99%) of the title compound as a light yellow liquid. Spectral data were the same as listed above for entry 1, Table 1.

Synthesis of 4-Acetyl-2'-methylbiphenyl (Table 5, entry 2).

Procedure A was followed, with 4'-bromoacetophenone (99.5 mg, 0.500 mmol), o-tolylboronic acid (81.6 mg, 0.600 mmol), K_3PO_4 (255 mg, 1.2 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (5.8 mg, 0.0200 mmol), and toluene (1 mL). At the conclusion of the reaction at room temperature, work up and column chromatography (10% Et_2O in hexane) yielded 102 mg (97%) of the title compound as a light yellow liquid. Spectral data were the same as listed above for entry 2, Table 1.

Synthesis of 4-Acetyl-4'-methoxybiphenyl (Table 5, entry 3).

Procedure B was followed, with 4'-bromoacetophenone (199 mg, 1.0 mmol), 4-methoxyphenylboronic acid (183 mg, 1.2 mmol), K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (0.02 M toluene solution; 0.100 mL, 0.020 mmol), and toluene (1.5 mL). After 6 hours at room temperature, work up and column chromatography (50% Et_2O in hexane) yielded 194 mg (99%) of

the title compound as a white solid. Spectral data were the same as listed above for entry 3, Table 1.

Synthesis of 4,4'-Diacetylbiphenyl (Table 5, entry 4).

Procedure B was followed, with 4'-bromoacetophenone (199 mg, 1.0 mmol), 4-acetylphenylboronic acid (197 mg, 1.2 mmol), K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (0.02 M toluene solution; 0.100 mL, 0.020 mmol), and toluene (2 mL) and THF (0.500 mL). At the conclusion of the reaction at 40 °C, work up and column chromatography (50% Et_2O in hexane) yielded 225 mg (99%) of the title compound as a white solid. Spectral data were the same as listed above for entry 4, Table 1.

Synthesis of 4-Methoxybiphenyl (Table 6, entry 1).

Procedure B was followed, using 4-bromoanisole (187 mg, 1.00 mmol), phenylboronic acid (146 mg, 1.20 mmol), K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.010 mmol), PA-Ph, ligand **15** (0.02 M toluene solution; 0.100 mL , 0.0200 mmol), and toluene (2 mL). After 3 hours at room temperature, work up and column chromatography (10% Et_2O in hexane) yielded 178 mg (97%) of the title compound as a pale yellow solid. Spectral data were the same as listed above for entry 1, Table 2.

Synthesis of 4-Methoxy-2'-methylbiphenyl (Table 6, entry 2).

Procedure B was followed, using 4-bromoanisole (187 mg, 1.00 mmol), o-tolylboronic acid (163 mg, 1.20 mmol), K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg,

0.010 mmol), PA-Ph, ligand **15** (0.02 M toluene solution; 0.100 mL , 0.0200 mmol), and toluene (2 mL). After 2 hours at room temperature, work up and column chromatography (10% Et_2O in hexane) yielded 188 mg (95%) of the title compound as a light yellow solid. Spectral data were the same as listed above for entry 2, Table 2.

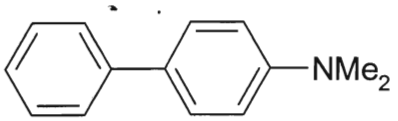
Synthesis of 4,4'-Dimethoxybiphenyl (Table 6, entry 3).

Procedure B was followed, using 4-bromoanisole (187 mg, 1.00 mmol), 4-methoxyphenylboronic acid (146 mg, 1.20 mmol), K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.010 mmol), PA-Ph, ligand **15** (0.02 M toluene solution; 0.100 mL , 0.0200 mmol), and toluene (2 mL). After 3 hours at room temperature, work up and column chromatography (20% EtOAc in hexane) yielded 209 mg (98%) of the title compound as a white solid. Spectral data were the same as listed above for entry 3, Table 2.

Synthesis of 4-Acetyl-4'-methoxybiphenyl (Table 6, entry 4).

Procedure B was followed, using 4-bromoanisole (187 mg, 1.00 mmol), 4-acetylphenylboronic acid (246 mg, 1.50 mmol), K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.010 mmol), PA-Ph, ligand **15** (0.02 M toluene solution; 0.100 mL , 0.0200 mmol), and toluene (2 mL), THF (0.500 mL) and water (0.200 mL). At the conclusion of the reaction at 40°C, work up and column chromatography (20% EtOAc in hexane) yielded 213 mg (94%) of the title compound as a white solid. Spectral data were the same as listed above for entry 4, Table 2.

Synthesis of 4-*N,N*-Dimethylaminobiphenyl (Table 7, entry 1).



Procedure A was followed, with 4-bromo-*N,N*-dimethylaniline (200 mg, 1.0 mmol), phenylboronic acid (146 mg, 1.2 mmol) K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (6 mg, 0.0200 mmol), and toluene (2 mL). After 6 hours at room temperature, work up and column chromatography (5% Et_2O in hexane) afforded 186 mg (94%) of the title compound as white solid.

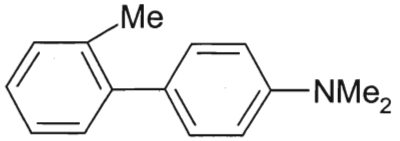
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.43-7.37 (m, 4H), 7.29-7.24 (m, 3H), 7.15-7.10 (m, 2H), 2.87 (s, 6H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 141.4, 129.6, 129.2, 129.1, 128.2, 127.6, 127.1, 113.7.

MS[EI+]: *m/z* (RI%): 197 (100), 196 (66.9), 152 (11.0).

MRMS: for $C_{14}H_{15}N$: calculated 197.12044, observed 197.12093.

Synthesis of 4-*N,N*-Dimethylamino-2'-methylbiphenyl (Table 7, entry 2).



Procedure A was followed, with 4-bromo-*N,N*-dimethylaniline (200 mg, 1.0 mmol), o-tolylboronic acid (190 mg, 1.4 mmol) K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (6 mg, 0.0200 mmol), and toluene (2 mL). After 2 hours at room temperature, work up and column chromatography (5% Et_2O in hexane) yielded 204 mg (97%) of the title compound as pale yellow liquid.

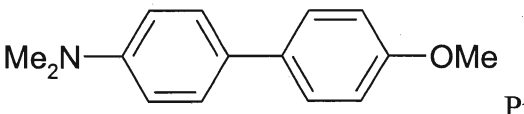
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.24-7.22 (m, 6H), 6.81 (d, J = 8.8 Hz, 2H), 2.99 (s, 6H), 2.31 (s, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 149.1, 141.9, 135.5, 131.7, 130.3, 130.0, 126.6, 125.7, 114.1, 112.4, 40.8, 20.7.

MS[EI+]: *m/z* (RI%): 211 (100), 195 (23), 165 (19), 105 (12).

HRMS: for $C_{15}H_{17}N$: calculated 211.13609, observed 211.13648.

Synthesis of 4-Methoxy-4'-*N,N*-dimethylaminobiphenyl (Table 7, entry 3).



Procedure A was followed, with 4-bromo-*N,N*-dimethylaniline (200 mg, 1.0 mmol), 4-methoxyphenylboronic acid (183 mg, 1.4 mmol) K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (6 mg, 0.0200 mmol), and toluene (2 mL). At the end of the reaction at room temperature, work up and column chromatography (50% Et_2O in hexane) yielded 219 mg (96%) of the title compound as pale yellow solid.

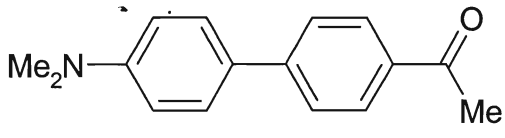
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.52-7.48 (m, 4H), 6.99-6.96 (m, 2H), 6.85 (d, J = 8.6 Hz, 2H), 3.87 (s, 3H), 3.02 (s, 6H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 158.7, 149.9, 134.3, 128.1, 127.7, 114.5, 113.4, 55.7, 41.2.

MS[EI+]: *m/z* (RI%): 227 (100), 212 (55), 113 (23).

HRMS: for $C_{15}H_{17}NO$: calculated 227.13101, observed 227.13116.

Synthesis of 4-Acetyl-4'-*N,N*-dimethylaminobiphenyl (Table 7, entry 4.



Procedure A was followed, with 4-bromo-*N,N*-dimethylaniline (200 mg, 1.0 mmol), 4-acetylphenylboronic acid (246 mg, 1.5 mmol) K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (6 mg, 0.0200 mmol), and toluene (2 mL). At the end of the reaction at 40oC, work up and column chromatography (20% Et_2O in hexane) yielded 222 mg (93%) of the title compound as light yellow solid.

^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.48-7.43 (m, 4H), 6.94-6.92 (m, 2H), 6.88 (d, J = 8.6 Hz, 2H), 3.81 (s, 3H), 2.96 (s, 6H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 197.7, 114.4, 136.6, 129.1, 129.0, 128.0, 127.5, 125.9, 112.6, 40.5, 26.8.

MS[EI+]: *m/z* (RI%): 239 (100), 224 (13), 210 (14), 196 (12).

HRMS: for $C_{16}H_{17}NO$: calculated 239.13101, observed 239.13061.

Synthesis of 2-Methylbiphenyl (Table 8, entry 1).

Procedure B was followed, using 2-bromotoluene (171 mg, 1.0 mmol), phenylboronic acid (146 mg, 1.2 mmol) K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (0.02 M toluene solution; 0.100 mL , 0.0200 mmol), and toluene (2 mL). After 2 hours at room temperature, work up and column chromatography (hexane) yielded 165 mg (98%) of the title compound as a pale yellow liquid. Spectral data were the same as listed above for entry 1, Table 4.

Synthesis of 2,2'-Dimethylbiphenyl (Table 8, entry 2).

Procedure B was followed, using 2-bromotoluene (171 mg, 1.0 mmol), o-tolylboronic acid (163 mg, 1.2 mmol) K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (0.02 M toluene solution; 0.100 mL , 0.0200 mmol), and toluene (2 mL). After 2 hours at room temperature, work up and column chromatography (hexane) yielded 182 mg (100%) of the title compound as a colourless liquid. Spectral data were the same as listed above for entry 2, Table 4

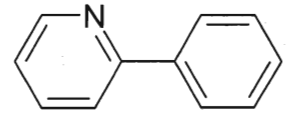
Synthesis of 4-Methoxy-2'-methylbiphenyl (Table 8, entry 3).

Procedure B was followed, using 2-bromotoluene (171 mg, 1.0 mmol), 4-methoxyphenylboronic acid (183 mg, 1.2 mmol) K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (0.02 M toluene solution; 0.100 mL , 0.0200 mmol), and toluene (2 mL). After 2 hours at room temperature, work up and column chromatography (10% EtOAc in hexane) yielded 194 mg (98%) of the title compound as a pale yellow liquid. Spectral data were the same as listed above for entry 3, Table 4.

Synthesis of 4-Acetyl-2'-methylbiphenyl (Table 8, entry 4).

Procedure B was followed, using 2-bromotoluene (171 mg, 1.0 mmol), 4-acetylphenylboronic acid (246 mg, 1.5 mmol) K_3PO_4 (509 mg, 2.4 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (0.02 M toluene solution; 0.100 mL , 0.0200 mmol), and toluene (2 mL), THF (1 mL) and water (0.500 mL). After 6 hours at 40 ^{o}C, work up and column chromatography (10% EtOAc in hexane)

yielded 199 mg (95%) of the title compound as a pale yellow liquid. Spectral data were the same as listed above for entry 4, Table 4.



Synthesis of 2-Phenylpyridine (Table 9, entry 1).

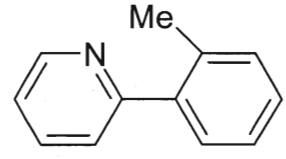
Procedure C was followed, using 2-chloropyridine (114 mg, 1.00 mmol), phenylboronic acid (146 mg, 1.20 mmol), Cs_2CO_3 (391, 1.2 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (7.3 mg, 0.0250 mmol), and toluene (2.5 mL). After 24 hours at room temperature, workup and column chromatography (10% EtOAc in hexane) afforded 142 mg (92%) of the title compound as light yellow liquid.

^{1}H NMR: ($CDCl_3$, 300 MHz): δ 8.72 (d, J = 4.6 Hz, 1H), 8.02 (d, J = 7.0 Hz, 2H), 7.75-7.73 (m, 2H), 7.53-7.41 (m, 4H), 7.25-7.20 (m, 1H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 157.8, 150.0, 137.2, 129.4, 129.2, 128.8, 127.3, 122.5, 121.0.

MS[EI+]: *m/z* (RI%): 155 (100), 154 (67), 127 (7), 77 (13).

HRMS: for $C_{11}H_9N$: calculated 155.07349, observed 155.07330.



Synthesis of 2-o-Tolylpyridine (Table 9, entry 2).

Procedure C was followed, using 2-chloropyridine (114 mg, 1.00 mmol), o-tolylboronic acid (163 mg, 1.20 mmol), Cs_2CO_3 (391, 1.2 mmol), $Pd_2(dba)_3.CHCl_3$ (20.7 mg, 0.0200 mmol), PA-Ph, ligand **15** (14.6 mg, 0.0500 mmol), and toluene (2.5

mL). After 24 hours at room temperature, workup and column chromatography (10% EtOAc in hexane) afforded 153 mg (90%) of the title compound as light yellow liquid.

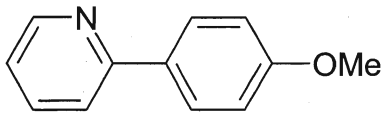
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 8.72 (d, J = 5.0 Hz, 1H), 7.77-7.72 (m, 2H), 7.45-7.40 (m, 2H), 7.33-7.23 (m, 3H), 2.40 (s, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 159.9, 149.1, 140.4, 136.2, 135.7, 130.7, 129.6, 128.4, 125.9, 124.1, 121.6, 20.7.

MS[EI+]: *m/z* (RI%): 169 (39), 168 (100), 168 (32), 83 (16).

HRMS: for $C_{12}H_{11}N$: calculated 169.08914, observed 169.08920.

Synthesis of 2-(4-Methoxyphenyl)pyridine (Table 9, entry 3).



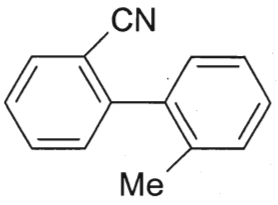
Procedure C was followed, using 2-chloropyridine (114 mg, 1.00 mmol), 4-methoxyphenylboronic acid (168 mg, 1.10 mmol), Cs_2CO_3 (391, 1.20 mmol), $Pd_2(dba)_3.CHCl_3$ (20.7 mg, 0.0200 mmol), PA-Ph, ligand **15** (14.6 mg, 0.0500 mmol), and toluene (2 mL). After 24 hours at room temperature, workup and column chromatography (20% EtOAc in hexane) afforded 165 mg (89%) of the title compound as light yellow liquid.

^{1}H NMR: ($CDCl_3$, 300 MHz): δ 8.44 (d, J = 4.5 Hz, 1H), 7.75-7.72 (m, 2H), 7.52-7.45 (m, 2H), 7.00-6.95 (m, 1H), 6.81-6.76 (m, 2H), 3.64 (s, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 160.6, 157.1, 149.4, 137.0, 131.8, 128.3, 121.6, 120.1, 114.2, 55.4.

MS[EI+]: *m/z* (RI%): 185 (100), 170 (16), 142 (27), 124 (24), 109 (20).

HRMS: for $C_{12}H_{11}NO$: calculated 185.08406, observed 185.08464.



Synthesis of 2-o-Tolylbenzonitrile (Table 9, entry 4).

Procedure C was followed, using 2-chlorobenzonitrile (69 mg, 0.500 mmol), o-tolylboronic acid (75 mg, 0.550 mmol), Cs_2CO_3 (326, 1.00 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (7.3 mg, 0.0250 mmol), and toluene (1.5 mL). After 24 hours at room temperature, workup and column chromatography (20% EtOAc in hexane) afforded 47 mg (70%) of the title compound as pale yellow liquid.

^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.80 (d, J = 8.4 Hz, 1H),7.69-7.64 (m, 1H), 7.51- 7.45 (m, 1H), 7.43-7.31 (m, 4H), 7.28 (d, 1H), 2.27 (s, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 146.2, 138.6, 136.1, 133.3, 133.0, 131.0, 130.9, 130.0, 129.2, 128.2, 126.4, 118.7, 113.2, 20.4.

MS[EI+]: *m/z* (RI%): 193 (100), 165 (31).

HRMS: for $C_{14}H_{11}N$: calculated 193.08914, observed 193.08868.

Synthesis of 4-Acetyl-4'-methoxybiphenyl (Table 9, entry 5).

Procedure C was followed, with 4'-chloroacetophenone (154 mg, 0.996 mmol), 4-methoxyphenylboronic acid (183 mg, 1.20 mmol), Cs_2CO_3 (391, 1.20 mmol), $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (7.3 mg, 0.0250 mmol), and toluene (1.5 mL). After 24 hours at room temperature, work up and column chromatography (50% Et_2O in hexane) yielded 207 mg (92%) of the title compound as a white solid. Spectral data were the same as listed above for entry 3, Table 1.

Synthesis of 4-Acetyl-2'-methylbiphenyl (Table 9, entry 6).

Procedure C was followed, with 4'-chloroacetophenone (77.3 mg, 0.500 mmol), o-tolylboronic acid (82 mg, 0.600 mmol), Cs_2CO_3 (326, 1.00 mmol), $Pd(OAc)_2$ (11.2 mg, 0.0500 mmol), PA-Ph, ligand **15** (29 mg, 0.0993 mmol), and toluene (1.5 mL). After 24 hours at room temperature, a small amount of the reaction mixture was flashed with dichloromethane through a micro-column, concentrated and a GC sample was prepared and the sample subjected to GC analysis. GC revealed 100% conversion. Mass spectrum obtained from the GC/MS was the same as listed in Table 1, entry 2.

Synthesis of 2-Methylbiphenyl (Table 10, entry 1).

Procedure C was followed, with 2-chlorotoluene (127 mg, 1.00 mmol), phenylboronic acid (146 mg, 1.20 mmol), K_3PO_4 (509 mg, 2.4 mmol), preformed catalyst, Pd(PA-Ph)$_2$-dba (24 mg, 0.0260 mmol), and toluene (3 mL). After 24 hours at 60oC, workup and column chromatography (hexane) yielded 148 mg (88%) of the title compound as a pale yellow liquid. Spectral data were the same as listed above for entry 1, Table 4.

Synthesis of 2,2'-Dimethylbiphenyl (Table 10, entry 2). Procedure C was followed, with 2-chlorotoluene (63 mg, 0.500 mmol), o-tolylboronic acid (75 mg, 0.550 mmol), K_3PO_4 (509 mg, 2.4 mmol), preformed catalyst, $Pd_2(dba)_3.CHCl_3$ (10.4 mg, 0.0100 mmol), PA-Ph, ligand **15** (7.3 mg, 0.0250 mmol) and toluene (1.5 mL). After 24 hours at 60°C, workup and column chromatography (hexane) yielded 84 mg (93%) of the title compound as a colorless liquid. Spectral data were the same as listed above for entry 2, Table 4.

Synthesis of 4-Methoxy-2'-methylbiphenyl (Table 10, entry 3).

Procedure C was followed, with 4-chloroanisole (143 mg, 1.00 mmol), o-tolylboronic acid (150 mg, 1.10 mmol), Cs_2CO_3 (391, 1.20 mmol), $Pd_2(dba)_3.CHCl_3$ (20.7 mg, 0.0200 mmol), PA-Ph, ligand **15** (34.5 mg, 0.0500 mmol) and toluene (1.5 mL). After 24 hours at 70 °C, workup and column chromatography (10% Et_2O in hexane) yielded 84 mg (93%) of the title compound as a colorless liquid. Spectral data were the same as listed above for entry 2, Table 2.

Synthesis of Preformed Catalyst: $Pd(PA\text{-}Ph)_2$-dba and $Pd(PA\text{-}Ph)_2O_2$.

$$Pd_2(dba)_3.CHCl_3 \quad + \quad 4\ PA\text{-}Ph \xrightarrow[rt,\ 2h]{toluene} Pd(PA\text{-}Ph)_2\text{-}dba + Pd(PA\text{-}Ph)_2O_2$$

To an oven dried round bottom flask was placed $Pd_2(dba)_3.CHCl_3$ (916 mg, 1.0 mmol), PA-Ph, ligand **15** (2340 mg, 8.0 mmol), and toluene (70 mL). The dark-purple mixture was stirred under argon for two hours. At the conclusion of the reaction, the original dark-purple colour is replaced with a yellow colour (indicative of free dba in solution). The reaction mixture is diluted to 10 folds with and allowed to stand overnight. Two kinds of crystals were formed; needle-like green-brown crystals {$Pd(PA\text{-}Ph)_2$-dba} and green microcrystals {$Pd(PA\text{-}Ph)_2O_2$}. The former is the major product. The two products, easily separated mechanically were obtained in greater than 90% yield.

Characterization of Pd(PA-Ph)$_2$-dba

^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.76 (d, J = 16 Hz, 2H), 7.74-7.63 (m, 8H), 7.45-7.37 (m, 6H), 7.22-7.17(m, 6H), 7.11 (d, J = 16 Hz, 2H), 2.81 (d, J = 4.4 Hz, 1H), 2.76 (d, J = 4.5 Hz, 1H,), 1.84-1.78 (m, 4H), 1.58-1.55 (m, 2H), 1.52 (s, 6H, 2 x gamma-CH_3), 1.47 (d, J = 14.5 Hz, 6H, 2 x α-CH_3), 1.33 (s, 6H, 2 x gamma-CH_3), 1.25 (d, J = 13.3 Hz, 6H, 2 x α-CH_3).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 189.0, 143.4, 135.2, 135.1, 133.3, 130.6, 129.1, 129.0, 128.7, 128.3, 125.5, {97.7, 97.0, 96.4, 96.3 (4 gamma -q Cs)}, {74.6, 74.2, 73.9, 72.9 (4 α-q Cs), {43.3, 40.3, 40.3, 39.2 (4 CH_2)}, 27.5 (4 gamma-CH_3), 21.3 (4 α-CH_3).

MS[FAB]: *m/z* (RI%): 692 (79.4), 691 (35.3), 690 (100), 689 (74.1), 688 (33.3).

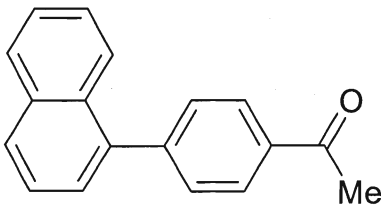
Characterization of Pd(PA-Ph)$_2$O$_2$

^{1}H NMR: (CDCl3, 300 MHz): δ 7.92-7.86 (m, 4H), 7.32-7.23 (m, 6H), 2.55 (d, J = 4.4 Hz, 1H), 2.50 (d, J = 4.4 Hz, 1H,), 1.71-1.56 (m, 6H), 1.48 (s, 6H, 2 x gamma-CH_3), 1.47 (d, J = 14.7 Hz, 6H, 2 x α-CH_3), 1.33 (s, 6H, 2 x gamma-CH_3), 1.04 (d, J = 13.3 Hz, 6H, 2 x α-CH_3).

^{13}C NMR: (CDCl3, 75 MHz): δ 2x 134.6, 2x 133.3, 2x 131.1, 2x 128.7 {96.7, 96.6, 96.2, 96.1 (4 gamma -q Cs)}, {74.5, 74.4, 74.0, 73.7 (4 α-q Cs), {43.8, 38.2 (4 CH_2)}, 27.7 (4 gamma-CH_3), 26.2 (4 α-CH_3).

MS[FAB]: *m/z* (RI%): 693 (29.3), 692 (79.4), 691 (35.3), 690 (100), 689 (74.1), 688 (33.3).

Synthesis of 4'-(1-Naphthyl)acetophenone (Equation 6 of Results & Discussion)



Procedure A was followed with 4-bromoacetophenone (199 mg, 1.00 mmol), 1-naphthalene boronic acid (142 mg, 1.20 mmol), $Pd(PA\text{-}Ph)_2$-dba (5 mg, 0.0050 mmol), K_3PO_4 (509 mg, 2.4 mmol) and toluene (3 mL). After 10 minutes, work up and column chromatography (20% EtOAc in hexane) yielded 245 mg (99%) of the title compound as a white solid.

^{1}H NMR: ($CDCl_3$, 300 MHz): δ 8.02 (d 2H), 7.85-7.74 (m, 3H), 7.52 (d, 2H), 7.48-7.33 (m, 4H), 2.60 (s, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 198.3, 146.2, 139.4, 136.4, 134.2, 131.6, 130.7, 129.4, 128.8, 128.7, 127.3, 126.8, 126.4, 126.0, 125.7, 27.1.

MS[EI+]: *m/z* (RI%): 246 (100), 231 (72), 202 (68).

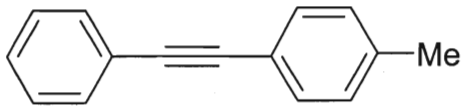
HRMS: for $C_{18}H_{14}O$: calculated 246.10446, observed 246.10509.

General Procedure for the Sonogashira Cross-Coupling Reactions

All liquid reagents (phenylacetylene, 2-methyl-3-butyn-2-ol and aryl iodides and aryl bromides) and solvents were degassed under argon prior to use. The palladium source, Cs_2CO_3, and CuI (if required) are placed in an oven dried reaction tube. The reaction tube is sealed with a rubber septum, evacuated and refilled with argon. Next, the aryl halide (if a liquid; if a solid, then the aryl halide is added prior to the evacuation-refill cycle), the alkyne and acetonitrile are added. The reaction is stirred under argon at the indicated temperature for the indicated amount of time. At the conclusion of the

reaction, the reaction mixture is diluted with Et_2O or EtOAc, filtered through a pad of silica gel with copious washings, concentrated, and purified by column chromatography on silica gel.

Synthesis of 4-Methylphenyl phenyl acetylene (Table 11, entry 1).



Following the general procedure, using Pd(PA-Ph)$_2$-dba (20.7 mg, 0.022 mmol), 4-bromotoluene (0.125 mL, 1.00 mmol), phenylacetylene (0.165 mL, 1.50 mmol), Cs_2CO_3 (476 mg, 1.46 mmol) and acetonitrile (1 mL). After 6 hours at 50°C, workup and column chromatography (hexane) yielded 178 mg (95%) of the title compound as a white solid.

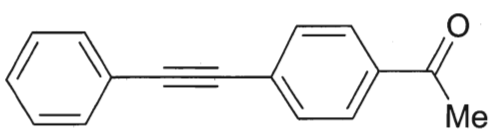
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.45-7.42 (m, 2H), 7.34 (d, J = 8.1 Hz, 2H), 7.24-7.21 (m, 3H), 7.05 (d, J = 8.0 Hz, 2H), 2.26 (s, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 138.8, 132.0, 131.9, 129.6, 128.8, 128.5, 123.9, 120.6, 90.0, 89.2, 21.9.

MS[EI+]: m/z (RI%): 192 (100), 191 (42).

HRMS: for $C_{15}H_{12}$: calculated 192.09390, observed 192.09396.

Synthesis of 4-Acetylphenyl phenyl acetylene (Table 11, entry 2).



Following the general procedure, using Pd(PA-Ph)$_2$-dba (20.7 mg, 0.022 mmol), 4-bromoacetophenone (198.5 mg, 0.997 mmol), phenylacetylene (0.165 mL, 1.50 mmol), Cs_2CO_3 (476 mg, 1.46 mmol) and

acetonitrile (1 mL). After 3 hours at 50°C, workup and column chromatography (10% EtOAc in hexane) yielded 196 mg (91%) of the title compound as a pale yellow solid.

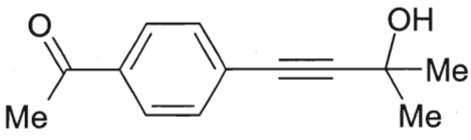
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.95 (d, J = 8.2 Hz, 2H), 7.62 (d, J = 8.3 Hz, 2H), 7.59-7.56 (m, 2H), 7.40-7.38 (m, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 197.7, 136.6, 132.1, 132.1, 129.2, 128.5, 128.7, 128.6, 123.0, 93.1, 89.0, 27.0.

MS[EI+]: *m/z* (RI%): 220 (72), 205 (100), 176 (38), 151 (17).

HRMS: for $C_{16}H_{12}O$: calculated 220.08881, observed 220.08910.

Synthesis of 4-(4-Acetylphenyl)-2-methyl-3-butyn-2-ol (Table 11, entry 3).



Following the general procedure, using Pd(PA-Ph)$_2$-dba (20.7 mg, 0.022 mmol), 4-bromoacetophenone (200 mg, 1.00 mmol), 2-methyl-3-butyn-2-ol (0.200 mL, 2.06 mmol), Cs_2CO_3 (476 mg, 1.46 mmol) and acetonitrile (1 mL). After 3 hours at 50°C, workup and column chromatography (10% EtOAc in hexane) yielded 183 mg (90%) of the title compound as a pale yellow liquid.

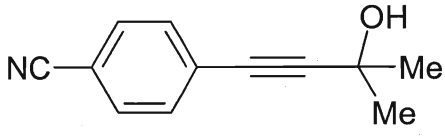
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.80 (d, J = 8.3 Hz, 2H), 7.40 (d, J = 8.3 Hz, 2H), 3.40 (s, broad, 1H), 2.53 (s, 3H), 1.59 (s, 6H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 198.2, 136.3, 132.1, 128.6, 128.5, 128.3, 97.9, 81.5, 78.0, 77.6, 77.1, 65.8, 65.6, 31.7, 26.9.

MS[EI+]: *m/z* (RI%): 202 (23), 187 (100).

HRMS: for $C_{13}H_{14}O_2$: calculated 202.09938, observed 202.09968.

Synthesis of 4-Cyanophenyl-2-methyl-3-butyn-2-ol (Table 11, entry 4).



Following the general procedure, using Pd(PA-Ph)$_2$-dba (20.7 mg, 0.022 mmol), 4-bromobenzonitrile (90 mg, 0.494 mmol), 2-methyl-3-butyn-2-ol (0.100 mL, 1.03 mmol), (*i*-Pr)$_2$NH (1 mL) and toluene (0.500 mL). After 20 hours at room temperature, workup and column chromatography (10% EtOAc in hexane) yielded 66 mg (74%) of the title compound as a pale yellow liquid.

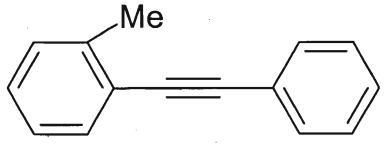
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.51 (d, J = 8.3 Hz, 2H), 7.41 (d, J = 8.4 Hz, 2H), 2.33 (s, broad, 1H), 1.55 (s, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ

MS[EI+]: *m/z* (RI%): 185 (14.8), 170 (100).

HRMS: for $C_{12}H_{11}NO_2$: calculated 201.07897, observed 185.08391.

Synthesis of Phenyl *o*-tolyl acetylene (Table 11, entry 5).



Following the general procedure, with Pd(PA-Ph)$_2$-dba (20.7 mg, 0.022 mmol), 2-bromotoluene (0.120 mL, 0.998 mmol), phenylacetylene (0.165 mL, 1.50 mmol), Cs_2CO_3 (488 mg, 1.50 mmol) and acetonitrile (1 mL). After 6 hours at 50°C, workup and column chromatography (hexane) yielded 179 mg (93%) of the title compound as a colourless liquid.

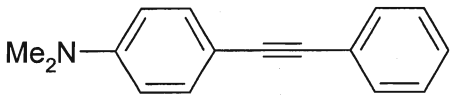
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.66-7.59 (m, 3H), 7.42-7.40 (m, 3H), 7.33-7.31 (m, 2H), 7.28-7.26 (m, 1H), 2.62 (s, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 140.6, 133.0, 132.3, 129.7, 128.9, 128.8, 128.7, 126.1, 124.0, 122.3, 93.8, 88.9, 21.2.

MS[EI+]: *m/z* (RI%): 192 (100), 191 (83), 165 (18), 115 (12).

HRMS: for $C_{15}H_{12}$: calculated 192.09390, observed 192.09437.

Synthesis of 4-*N,N*-Dimethylaminophenyl phenyl acetylene (Table 11, entry 6).



Following the general procedure, with Pd(PA-Ph)$_2$-dba (20.7 mg, 0.022 mmol), 4-bromo-N,N-dimethylaniline (174.6 mg, 0.873 mmol), phenylacetylene (0.165 mL, 1.50 mmol), Cs_2CO_3 (427mg, 1.31 mmol) and acetonitrile (1 mL). After 8 hours at 50°C, workup and column chromatography (2% EtOAc in hexane) yielded 176 mg (91%) of the title compound as a light yellow solid.

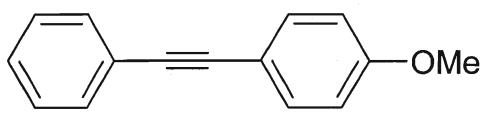
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.55-7.52 (m, 2H), 7.46-7.44 (m, 2H), 7.36-7.32 (m, 3H), 7.69 (d, J = 8.8 Hz, 2H), 3.02 (s, 6H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 150.5, 133.1, 131.7, 128.6, 127.8, 124.6, 112.2, 110.4, 91.0, 87.7, 40.6.

MS[EI+]: *m/z* (RI%): 221 (100), 220 (45), 110 (21).

HRMS: for $C_{16}H_{15}N$: calculated 221.12044, observed 221.12100.

Synthesis of 4-Methoxyphenyl phenyl acetylene (Table 11, entry 7).



Following the general procedure, using Pd(PA-Ph)$_2$-dba (20.7 mg, 0.022 mmol), 4-bromoanisole (0.125 mL, 1.00 mmol),

phenylacetylene (0.165 mL, 1.50 mmol), Cs_2CO_3 (488 mg, 1.50 mmol) and acetonitrile (1 mL). After 6 hours at 60°C, workup and column chromatography (2% EtOAc in hexane) yielded 188 mg (90%) of the title compound as a pale yellow solid.

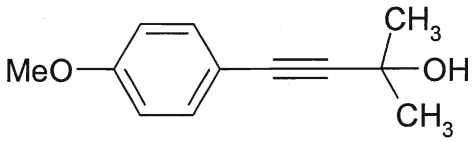
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.61-7.53 (m, 4H), 7.40-7.36 (m, 3H), 6.95-6.92 (m, 2H), 3.85 (s, 2H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 160.1, 133.6, 131.9, 128.7, 128.6, 124.0, 115.8, 114.5, 89.9, 88.6, 55.8.

MS[EI+]: *m/z* (RI%): 208 (100), 193 (28), 165 (16).

HRMS: for $C_{15}H_{12}O$: calculated 208.08881, observed 208.08861.

Synthesis of 4-(4-Methoxyphenyl)-2-methyl-3-butyn-2-ol (Table 11, entry 8).



Following the general procedure, using Pd(PA-Ph)$_2$-dba (20.7 mg, 0.022 mmol), 4-bromoanisole (0.125 mL, 1.00 mmol), 2-methyl-3-butyn-2-ol (0.195 mL, 2.00 mmol), Cs_2CO_3 (391 mg, 1.20 mmol) and acetonitrile (1 mL). At the conclusion of the reaction, at 50°C, workup and column chromatography (10% EtOAc in hexane) yielded 175 mg (92%) of the title compound as a yellow liquid.

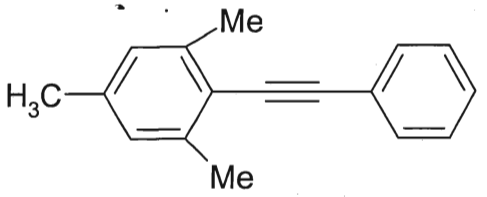
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.35 (d, J = 8.8 Hz, 2H), 6.82 (d, J = 8.8 Hz, 2H), 3.80 (s, 3H), 3.40 (s, broad, 1H), 1.62 (s, 6H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 159.9, 133.4, 115.2, 114.2, 92.9, 82.4, 66.0,55.6, 32.0.

MS[EI+]: *m/z* (RI%):190 (52), 175 (100).

HRMS: for $C_{12}H_{14}O_2$: calculated 190.09938, observed 190.09916.

Synthesis of 2,4,6-Trimethylphenyl phenyl acetylene, (Table 11, entry 9).



Following the general procedure, using Pd(PA-Ph)$_2$-dba (20.7 mg, 0.022 mmol), 2,4,6-mesitylbromide (195 mg, 0.980 mmol), phenylacetylene (0.165 mL, 1.50 mmol), Cs_2CO_3 (479 mg, 1.47 mmol) and acetonitrile (1 mL). After 12 hours at 50°C, workup and column chromatography hexane) afforded 201 mg (93%) of the title compound as a colourless liqquid.

^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.71 (m, 2H), 7.48 (m, 3H), 7.05 (s, 2H), 2.67 (s, 6H), 2.45 (s, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 140.6, 138.3, 131.9, 129.0, 128.7, 128.4, 126.8, 120.5, 97.7, 88.0, 21.9, 21.6.

MS[EI+]: *m/z* (RI%): 220 (100), 205 (41).

HRMS: for $C_{17}H_{16}$: calculated 220.12520, observed 220.12517.

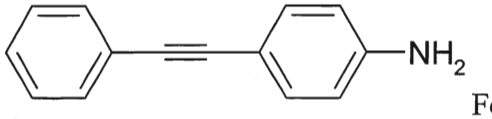
Synthesis of 4-Methylphenyl phenyl acetylene (Table 12, entry 1).

Following the general procedure, using Pd(PA-Ph)$_2$-dba (14 mg, 0.015 mmol), 4-iodotoluene (218 mg, 1.00 mmol), phenylacetylene (0.165 mL, 1.50 mmol), CuI (4 mg, 0.02 mmol), (*i*-Pr)$_2$NEt (0.210 mL, 1.20 mmol), and acetonitrile (1 mL). After 1 hour at room temperature, workup and column chromatography (hexane) yielded 188 mg (96%) of the title compound as a white solid. Spectral data were the same as listed for Table 11, entry 1.

Synthesis of 4-Acetylphenyl phenyl acetylene (Table 12, entry 2).

Following the general procedure, using $Pd(PA\text{-}Ph)_2$-dba (14 mg, 0.015 mmol), 4-iodoacetophenone (246 mg, 1.00 mmol), phenylacetylene (0.165 mL, 1.50 mmol), CuI (4 mg, 0.02 mmol), $(i\text{-}Pr)_2NEt$ (0.210 mL, 1.20 mmol), and acetonitrile (2 mL). After 1 hour at room temperature, workup and column chromatography (10% EtOAc in hexane) yielded 204 mg (93%) of the title compound as a pale yellow solid. Spectral data were the same as listed for Table 11, entry 2

Synthesis of aniline phenyl acetylene (Table 12, entry 3).



Following the general procedure, using $Pd(PA\text{-}Ph)_2$-dba (14 mg, 0.015 mmol), 4-iodoaniline (218 mg, 0.997 mmol), phenylacetylene (0.165 mL, 1.50 mmol), CuI (4 mg, 0.020 mmol), $(i\text{-}Pr)_2NEt$ (0.210 mL, 1.20 mmol), and acetonitrile (1 mL). After 1 hour at room temperature, workup and column chromatography (10% EtOAc in hexane) yielded 176 mg (91%) of the title compound as a yellow solid.

^1H NMR: ($CDCl_3$, 300 MHz): δ 7.65-7.61 (m, 3H), 7.50-7.40 (m, 4H), 7.77 (d, $J = 8.7$ Hz, 2H), 3.93 (s, broad, 2H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 147.0, 133.4, 131.8, 128.7, 128.1, 124.3, 115.2, 113.0, 90.5, 87.7.

MS[EI+]: *m/z* (RI%): 193 (100), 165 (12.6).

HRMS: for $C_{14}H_{11}N$: calculated 193.08914, observed 193.08851.

Synthesis of phenyl *o*-tolyl acetylene (Table 12, entry 4).

Following the general procedure, with Pd(PA-Ph)$_2$-dba (14 mg, 0.015 mmol), 2-iodotoluene (0.125 mL, 0.982 mmol), phenylacetylene (0.165 mL, 1.50 mmol), CuI (4 mg, 0.020 mmol), (*i*-Pr)$_2$NEt (0.210 mL, 1.20 mmol), and acetonitrile (1 mL). After 1 hour at room temperature, workup and column chromatography (hexane) yielded 173 mg (93%) of the title compound as a colourless liquid. Spectral data were the same as listed for Table 12, entry 5.

Synthesis of 4-methoxyphenyl phenyl acetylene (Table 12, entry 5).

Following the general procedure, using Pd(PA-Ph)$_2$-dba (14 mg, 0.015 mmol), 4-iodoanisole (234 mg, 1.00 mmol), phenylacetylene (0.165 mL, 1.50 mmol), CuI (4 mg, 0.020 mmol), (*i*-Pr)$_2$NEt (0.210 mL, 1.20 mmol), and acetonitrile (1 mL). After 1 hour at room temperature, workup and column chromatography (2% EtOAc in hexane) yielded 196 mg (94%) of the title compound as a pale yellow solid. Spectral data were the same as listed for Table 11, entry 7.

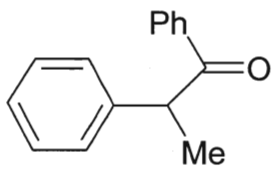
Synthesis of 4-(4-methoxyphenyl)-2-methyl-3-butyn-2-ol (Table 12, entry 6).

Following the general procedure, using Pd(PA-Ph)$_2$-dba (14 mg, 0.015 mmol), 4-iodoanisole (234 mg, 1.00 mmol), 2-methyl-3-butyn-2-ol (0.150 mL, 1.50 mmol), CuI (4 mg, 0.020 mmol), (*i*-Pr)$_2$NEt (0.210 mL, 1.20 mmol), and acetonitrile (1 mL). After 1 hour at room temperature, workup and column chromatography (10% EtOAc in hexane) yielded 175mg (92%) of the title compound as a yellow liquid. Spectral data were the

same as listed for Table 11, entry 8.

General Procedure for the Pd(PA-Ph)$_2$-dba Catalyzed Ketone Arylation Reaction.

Pd(PA-Ph)$_2$-dba (14 mg, 0.015 mmol), NaO^{t}Bu (144 mg, 1.500 mmol) and aryl bromide (if a solid) are placed in a reaction tube containing a magnetic stir bar. The reaction tube is evacuated and then refilled with argon. Next, toluene (1 mL) is added followed by the aryl halide (if a liquid), ketone and the remaining toluene (2 mL). The reaction is stirred at the indicated temperature for the indicated amount of time (the reaction is monitored by ^{1}H NMR). At the conclusion of the reaction, the reaction mixture is diluted with CH_2Cl_2 or EtOAc, filtered through a pad of silica gel with copious washings, concentrated, and purified by column chromatography on silica gel (hexane/EtOAc).



Synthesis of 1,2-diphenyl-1-propanone (Table 13, entry 12).

Pd(PA-Ph)$_2$-dba (20.7 mg, 0.022 mmol), NaO^{t}Bu (192 mg, 2.00 mmol), Bromobenzene (157 mg, 1.00 mmol), propiophenone (152 mg 1.13 mmol) and toluene (2 mL) were used. Reaction at 25 °C for 24 h gave 195 mg (93%) of the title compound as a pale yellow liquid after silica gel chromatography (hexane/EtOAc = 95/5).

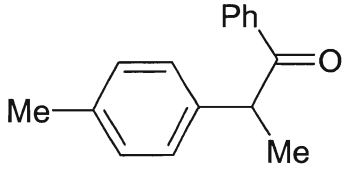
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 8.00 (d, J = 7.2 Hz, 2H), 7.47 (t, 1H), 7.42-7.40 (M, 2H), 7.38-7.33 (m, 4H), 7.22 (m, 1H), 4.73 (q = 1H), 1.59 (d, J = 6.8 Hz, 3H).

^{13}C NMR: (CDCl3, 75 MHz): δ 200.7, 141.9, 136.9, 133.2, 129.4, 129.2, 128.9, 128.2, 127.3, 48.3, 20.0.

MS[EI+]: *m/z* (RI%): 210 (4), 105 (100).

HRMS: for $C_{15}H_{14}O$: calculated 210.10446, observed 210.10455.

Synthesis of 2-(4-methylphenyl)-1-phenyl-1-propanone (Table 13, entry 2).



$Pd(PA\text{-}Ph)_2$-dba (14.0 mg, 0.015 mmol), NaO^tBu (192 mg, 2.00 mmol), 4-Bromotoluene (171 mg, 1.00 mmol), propiophenone (152 mg 1.13 mmol) and toluene (2 mL) were used. Reaction at 30 °C for 24 h gave 208 mg (96%) of the title compound as a pale yellow liquid after silica gel chromatography (hexane/EtOAc = 95/5).

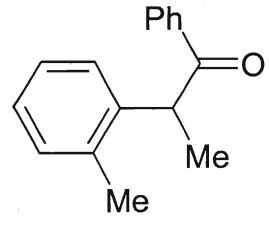
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 8.03 (d, J = 7.4 Hz, 2H), 7.50 (t, 1H), 7.42 (t, 2H), 7.26 (d, J = 8.1 Hz, 2H), 7.15 (d, J = 8.0 Hz, 2H), 4.75 (q, 1H), 2.33 (s, 3H), 1.61 (d, J = 6.9 Hz, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 200.8, 138.9, 137.0, 136.9, 133.2, 130.2, 129.2, 128.9, 128.1, 47.9, 21.4, 20.0.

MS[EI+]: *m/z* (RI%): 224 (6), 119 (54), 105 (100).

HRMS: for $C_{16}H_{16}O$: calculated 224.12011, observed 224.11990.

Synthesis of 2-(2-methylphenyl)-1-phenyl-1-propanone (Table 13, entry 3).



$Pd(PA\text{-}Ph)_2$-dba (14.0 mg, 0.015 mmol), NaO^tBu (192 mg, 2.00

mmol), 2-Bromotoluene (171 mg, 1.00 mmol), propiophenone (152 mg 1.13 mmol) and toluene (2 mL) were used. Reaction at 30 °C for 15 h gave 206 mg (95%) of the title compound as a pale yellow liquid after silica gel chromatography (hexane/EtOAc = 95/5).

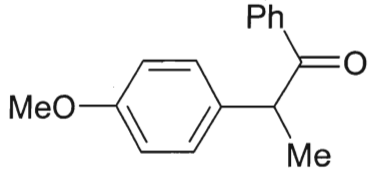
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.70 (d, 2H), 7.28 (t, 1H), 7.19 (t, 2H), 7.06 (t, 1H), 6.98-6.92 (m, 3H), 2.36 (s, 3H), 4.63 (q, 3.8 Hz, 1H), 1.35 (d, J = 6.8 Hz, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 201.4, 140.6, 137.0, 135.0, 133.1, 131.4, 128.9, 127.4, 127.3, 127.2, 45.0, 20.1, 18.5.

MS[EI+]: *m/z* (RI%): 224 (14), 119 (24), 105 (105).

HRMS: for $C_{16}H_{16}O$: calculated 224.12011, observed 224.12012.

Synthesis of 2-(4-methoxyphenyl)-1-phenyl-1-propanone (Table 13, entry 4).



$Pd(PA\text{-}Ph)_2$-dba (14.0 mg, 0.015 mmol), NaO^tBu (192 mg, 2.00 mmol), 2-Bromoanisole (187 mg, 1.00 mmol), propiophenone (152 mg 1.13 mmol) and toluene (3 mL) were used. Reaction at 30 °C for 24 h gave 237 mg (99%) of the title compound as a pale yellow liquid after silica gel chromatography (hexane/EtOAc = 95/10).

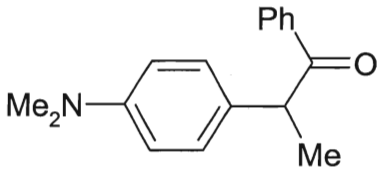
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.82 (d, 2H), 7.30 (t, 1H), 7.22 (t, 2H), 7.10 (d, 2H), 6.70 (d, 2H), 4.53 (q, 1H), 3.56 (s, 3H), 1.37 (d, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 200.9, 158.9, 136.9, 133.9, 133.2, 129.2, 129.2, 128.9, 114.8, 55.5, 47.3, 20.0.

MS[EI+]: *m/z* (RI%): 240 (6), 135 (100).

HRMS: for $C_{16}H_{16}O_2$: calculated 240.11503, observed 240.11586.

Synthesis of 2-(4-*N*,*N*-dimethylaminophenyl)-1-phenyl-1-propanone (Table 13, entry 5).



Pd(PA-Ph)$_2$-dba (14.0 mg, 0.015 mmol), NaO^{t}Bu (192 mg, 2.00 mmol), 4-Bromo-N,N-dimethylaniline (200 mg, 1.00 mmol), propiophenone (152 mg 1.13 mmol) and toluene (3 mL) were used. Reaction at 30 °C for 24 h gave 248 mg (98%) of the title compound as a pale yellow solid after silica gel chromatography (hexane/EtOAc = 95/10).

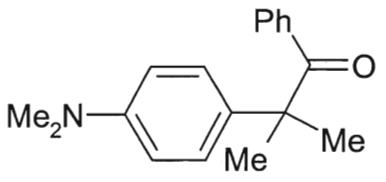
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.83 (d, 2H), 7.28-7.20 (m, 3H), 7.04 (d, 2H), 6.52 (2H), 4.47 (q, 1H), 2.72 (s, 6H), 1.38 (d, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 201.1, 149.9, 137.2, 133.0, 129.5, 129.2, 128.9, 128.8, 113.4, 47.3, 40.9, 19.9.

MS[EI+]: *m/z* (RI%): 253 (7), 148 (100).

HRMS: for $C_{17}H_{19}NO$: calculated 253.14666, observed 253.14682.

Synthesis of 2-(4-*N,N*-dimethylaminophenyl)-2-methyl-1-phenyl-1-propanone, (Table 13, entry 6).



$Pd(PA\text{-}Ph)_2$-dba (14.0 mg, 0.015 mmol), NaO^tBu (192 mg, 2.00 mmol), 4-Bromo-N,N-dimethylaniline (200 mg, 1.00 mmol), isobutyrophenone (166 mg 1.12 mmol) and toluene (3 mL) were used. Reaction at 50 °C for 24 h gave 232 mg (87%) of the title compound as a pale yellow solid after silica gel chromatography (hexane/EtOAc = 95/10).

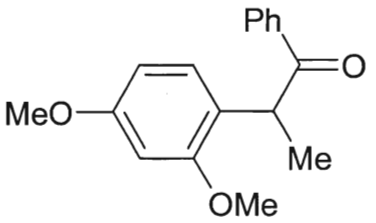
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.56 (d, J = 7.2 Hz, 2H), 7.37 (t, 1H), 7.24 (m, 4H), 6.76 (d, J = 8.8 Hz, 2H), 2.97 (s, 6H), 1.60 (s, 6H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 204.9, 149.7, 137.2, 133.0, 131.8, 130.0, 128.3, 126.9, 113.4, 50.8, 40.9, 28.2.

MS[EI+]: *m/z* (RI%): 267 (3.3), 162 (100).

HRMS: for $C_{18}H_{21}NO$: calculated 267.16231, observed 267.16265.

Synthesis of 2-(2,4-dimethoxyphenyl)-1-phenyl-1-propanone, (Table 13, entry 7).



$Pd(PA\text{-}Ph)_2$-dba (14.0 mg, 0.015 mmol), NaO^tBu (144 mg, 1.50 mmol), 1-Bromo-2,4-dimethoxybenzene (217 mg, 1.00 mmol), propiophenone (152 mg 1.13 mmol) and toluene (3 mL) were used. Reaction at 40 °C for 24 h gave 217 mg (80%) of the title compound as a pale yellow liquid after silica gel chromatography

(hexane/EtOAc = 95/10).

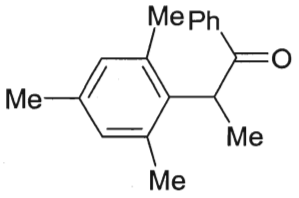
^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.97 (d, J = 7.8 Hz, 2H), 7.47 9m, 1H), 7.40 (m, 2H), 7.04 (d, J = 8.4 Hz, 2H), 6.48 (s, 1H), 6.42 (q, 1H), 3.87 (s, 3H), 3.8 (s, 3H). 1.47 (d, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 201.9, 160.1, 157.1, 137.0, 132.9, 128.9, 128.9, 128.8, 128.7, 122.9, 105.0, 99.3, 55.9, 55.6, 40.1, 18.2.

MS[EI+]: *m/z* (RI%): 270 (3), 165 (100).

HRMS: for $C_{17}H_{18}O_3$: calculated 270.12559, observed 270.12604.

Synthesis of 2-(2,4,6-Trimethylphenyl)-1-phenyl-1-propanone, (Table 13, entry 8).



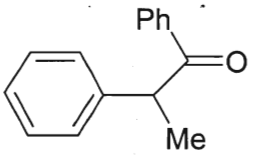
$Pd(PA\text{-}Ph)_2$-dba (14.0 mg, 0.015 mmol), NaO^tBu (144 mg, 1.50 mmol), 2,4,6-mesitylbromide (199.1 mg, 1.00 mmol), propiophenone (152 mg 1.13 mmol) and toluene (3 mL) were used. Reaction at 40 °C for 24 h gave 219 mg (87%) of the title compound as a pale yellow liquid after silica gel chromatography (hexane/EtOAc = 95/5).

^{1}H NMR: ($CDCl_3$, 300 MHz): δ 7.77 (d, J = 7.8 Hz, 2H), 7.42 (m, 1H), 7.31 9m, 2H), 6.83 (s, 2H), 4.54 (q, 1H), 2.30 (s, 3H), 2.24 (s, 6H), 1.53 (d, J = 6.8 Hz, 3H).

^{13}C NMR: ($CDCl_3$, 75 MHz): δ 202.9, 137.3, 137.2, 136.5, 135.8, 132.8, 130.7, 128.9, 128.6, 46.2, 21.1, 20.9, 15.4.

MS[EI+]: *m/z* (RI%): 252 (16), 147 (100), 105 (267).

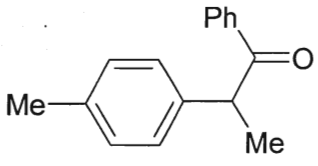
HRMS: for $C_{18}H_{20}O$: calculated 252.15141, observed 252.15169.



Synthesis of 1,2-Diphenyl-1-propanone (Table 13, entry 12).

$Pd(PA\text{-}Ph)_2$-dba (20.7 mg, 0.022 mmol), NaO^tBu (192 mg, 2.00 mmol), Chlorobenzene (113 mg, 1.00 mmol), propiophenone (152 mg 1.13 mmol) and toluene (2 mL) were used. Reaction at 70 °C for 24 h gave 158 mg (75%) of the title compound as a pale yellow liquid after silica gel chromatography (hexane/EtOAc = 95/5). Spectral data were the same as listed for table 13, entry 1.

Synthesis of 2-(4-Methylphenyl)-1-phenyl-1-propanone (Table 13, entry 10).



$Pd(PA\text{-}Ph)_2$-dba (14.0 mg, 0.015 mmol), NaO^tBu (192 mg, 2.00 mmol), 4-Chlorotoluene (127 mg, 1.00 mmol), propiophenone (152 mg 1.13 mmol) and toluene (2 mL) were used. Reaction at 70 °C for 24 h gave 175 mg (96%) of the title compound as a pale yellow liquid after silica gel chromatography (hexane/EtOAc = 95/5).

Spectral data were the same as listed for table 13, entry 2.

APPENDIX I: Tables of X-Ray Crystallography for 1,3,5,7-tetra-methyl-2,4,8-trioxa-6-phosphaadamantane

Table I-1. Crystal data and structure refinement for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-phosphaadamantane.

Empirical formula	$C_{10}H_{17}O_3P_1$	
Formula weight	216.21	
Temperature	123(1) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	$P2_1/c$	
Unit cell dimensions	a = 8.1422(3) Å	α= 90°.
	b = 8.0756(2) Å	β= 94.155(1)°.
	c = 16.6229(5) Å	γ = 90°.
Volume	1090.14(6) $Å^3$	
Z	4	
Density (calculated)	1.317 Mg/m^3	
Absorption coefficient	0.232 mm^{-1}	
$F(000)$	464	
Crystal size	0.45 x 0.30 x 0.25 mm^3	
Theta range for data collection	2.46 to 26.37°.	
Index ranges	-9<=h<=10, -10<=k<=10, -20<=l<=20	
Reflections collected	9074	
Independent reflections	2231 [R(int) = 0.0142]	
Completeness to theta = 26.37°	100.0 %	
Absorption correction	None	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	2231 / 0 / 151	
Goodness-of-fit on F^2	1.002	
Final R indices [$I > 2\sigma(I)$]	R_1 = 0.0300, wR^2 = 0.0838	
R indices (all data)	R_1 = 0.0307, wR^2 = 0.0845	
Extinction coefficient	none	
Largest diff. peak and hole	0.387 and -0.229 e.$Å^{-3}$	

Table I-2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-phosphaadamantane. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
P(1)	2075(1)	6717(1)	3010(1)	24(1)
O(1)	3101(1)	9835(1)	3408(1)	19(1)
O(2)	2509(1)	9676(1)	4768(1)	19(1)
O(3)	1553(1)	6937(1)	4618(1)	19(1)
C(1)	3750(1)	8161(1)	3399(1)	19(1)
C(2)	1879(1)	10117(2)	3971(1)	19(1)
C(3)	324(1)	9098(2)	3769(1)	20(1)
C(4)	717(1)	7253(2)	3832(1)	19(1)
C(5)	5139(2)	8212(2)	2841(1)	25(1)
C(6)	1565(2)	11955(2)	3970(1)	25(1)
C(7)	-812(2)	6175(2)	3789(1)	26(1)
C(8)	4327(1)	7674(2)	4260(1)	19(1)
C(9)	2954(1)	7962(1)	4821(1)	19(1)
C(10)	3466(2)	7611(2)	5695(1)	24(1)

Table I-3. Selected bond lengths [Å] and angles [°] for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-phosphaadamantane.

P(1)-C(4)	1.8713(12)
P(1)-C(1)	1.8735(12)
O(1)-C(2)	1.4330(14)
O(1)-C(1)	1.4517(14)
O(2)-C(2)	1.4304(14)
O(2)-C(9)	1.4322(14)
O(3)-C(9)	1.4294(14)
O(3)-C(4)	1.4515(14)
C(1)-C(5)	1.5143(16)
C(1)-C(8)	1.5257(16)
C(2)-C(6)	1.5060(16)
C(2)-C(3)	1.5270(16)
C(3)-C(4)	1.5262(16)
C(4)-C(7)	1.5166(16)
C(8)-C(9)	1.5250(16)
C(9)-C(10)	1.5081(16)
P(1)-H(1A)	1.28(3)
C(4)-P(1)-C(1)	93.29(5)
C(2)-O(1)-C(1)	115.18(9)
C(2)-O(2)-C(9)	111.69(9)
C(9)-O(3)-C(4)	115.15(9)
O(1)-C(1)-C(5)	105.66(9)
O(1)-C(1)-C(8)	108.51(9)
C(5)-C(1)-C(8)	112.86(10)
O(1)-C(1)-P(1)	109.08(7)
C(5)-C(1)-P(1)	111.25(8)
C(8)-C(1)-P(1)	109.33(8)
O(2)-C(2)-O(1)	110.24(9)
O(2)-C(2)-C(6)	107.24(10)
O(1)-C(2)-C(6)	106.33(10)
O(2)-C(2)-C(3)	107.83(9)
O(1)-C(2)-C(3)	111.98(9)

C(6)-C(2)-C(3)	113.13(10)
C(4)-C(3)-C(2)	110.15(9)
O(3)-C(4)-C(7)	105.77(9)
O(3)-C(4)-C(3)	108.44(9)
C(7)-C(4)-C(3)	112.95(10)
O(3)-C(4)-P(1)	110.70(7)
C(7)-C(4)-P(1)	111.07(8)
C(3)-C(4)-P(1)	107.90(8)
C(9)-C(8)-C(1)	110.17(9)
O(3)-C(9)-O(2)	110.57(9)
O(3)-C(9)-C(10)	106.19(9)
O(2)-C(9)-C(10)	106.97(9)
O(3)-C(9)-C(8)	112.05(9)
O(2)-C(9)-C(8)	107.64(9)
C(10)-C(9)-C(8)	113.33(10)
C(4)-P(1)-H(1A)	98.5(14)
C(1)-P(1)-H(1A)	100.7(14)

Table I-4. Bond lengths [Å] and angles [°] for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-phosphaadamantane.

P(1)-C(4)	1.8713(12)
P(1)-C(1)	1.8735(12)
O(1)-C(2)	1.4330(14)
O(1)-C(1)	1.4517(14)
O(2)-C(2)	1.4304(14)
O(2)-C(9)	1.4322(14)
O(3)-C(9)	1.4294(14)
O(3)-C(4)	1.4515(14)
C(1)-C(5)	1.5143(16)
C(1)-C(8)	1.5257(16)
C(2)-C(6)	1.5060(16)
C(2)-C(3)	1.5270(16)
C(3)-C(4)	1.5262(16)
C(4)-C(7)	1.5166(16)
C(8)-C(9)	1.5250(16)
C(9)-C(10)	1.5081(16)
P(1)-H(1A)	1.28(3)
C(3)-H(3A)	0.9900
C(3)-H(3B)	0.9900
C(5)-H(5A)	0.9800
C(5)-H(5B)	0.9800
C(5)-H(5C)	0.9800
C(6)-H(6A)	0.9800
C(6)-H(6B)	0.9800
C(6)-H(6C)	0.9800
C(7)-H(7A)	0.9800
C(7)-H(7B)	0.9800
C(7)-H(7C)	0.9800
C(8)-H(8A)	0.9900
C(8)-H(8B)	0.9900
C(10)-H(10A)	0.9800
C(10)-H(10B)	0.9800
C(10)-H(10C)	0.9800

C(4)-P(1)-C(1)	93.29(5)
C(2)-O(1)-C(1)	115.18(9)
C(2)-O(2)-C(9)	111.69(9)
C(9)-O(3)-C(4)	115.15(9)
O(1)-C(1)-C(5)	105.66(9)
O(1)-C(1)-C(8)	108.51(9)
C(5)-C(1)-C(8)	112.86(10)
O(1)-C(1)-P(1)	109.08(7)
C(5)-C(1)-P(1)	111.25(8)
C(8)-C(1)-P(1)	109.33(8)
O(2)-C(2)-O(1)	110.24(9)
O(2)-C(2)-C(6)	107.24(10)
O(1)-C(2)-C(6)	106.33(10)
O(2)-C(2)-C(3)	107.83(9)
O(1)-C(2)-C(3)	111.98(9)
C(6)-C(2)-C(3)	113.13(10)
C(4)-C(3)-C(2)	110.15(9)
O(3)-C(4)-C(7)	105.77(9)
O(3)-C(4)-C(3)	108.44(9)
C(7)-C(4)-C(3)	112.95(10)
O(3)-C(4)-P(1)	110.70(7)
C(7)-C(4)-P(1)	111.07(8)
C(3)-C(4)-P(1)	107.90(8)
C(9)-C(8)-C(1)	110.17(9)
O(3)-C(9)-O(2)	110.57(9)
O(3)-C(9)-C(10)	106.19(9)
O(2)-C(9)-C(10)	106.97(9)
O(3)-C(9)-C(8)	112.05(9)
O(2)-C(9)-C(8)	107.64(9)
C(10)-C(9)-C(8)	113.33(10)
C(4)-P(1)-H(1A)	98.5(14)
C(1)-P(1)-H(1A)	100.7(14)
C(4)-C(3)-H(3A)	109.6
C(2)-C(3)-H(3A)	109.6
C(4)-C(3)-H(3B)	109.6
C(2)-C(3)-H(3B)	109.6

H(3A)-C(3)-H(3B)	108.1
C(1)-C(5)-H(5A)	109.5
C(1)-C(5)-H(5B)	109.5
H(5A)-C(5)-H(5B)	109.5
C(1)-C(5)-H(5C)	109.5
H(5A)-C(5)-H(5C)	109.5
H(5B)-C(5)-H(5C)	109.5
C(2)-C(6)-H(6A)	109.5
C(2)-C(6)-H(6B)	109.5
H(6A)-C(6)-H(6B)	109.5
C(2)-C(6)-H(6C)	109.5
H(6A)-C(6)-H(6C)	109.5
H(6B)-C(6)-H(6C)	109.5
C(4)-C(7)-H(7A)	109.5
C(4)-C(7)-H(7B)	109.5
H(7A)-C(7)-H(7B)	109.5
C(4)-C(7)-H(7C)	109.5
H(7A)-C(7)-H(7C)	109.5
H(7B)-C(7)-H(7C)	109.5
C(9)-C(8)-H(8A)	109.6
C(1)-C(8)-H(8A)	109.6
C(9)-C(8)-H(8B)	109.6
C(1)-C(8)-H(8B)	109.6
H(8A)-C(8)-H(8B)	108.1
C(9)-C(10)-H(10A)	109.5
C(9)-C(10)-H(10B)	109.5
H(10A)-C(10)-H(10B)	109.5
C(9)-C(10)-H(10C)	109.5
H(10A)-C(10)-H(10C)	109.5
H(10B)-C(10)-H(10C)	109.5

Table I-5. Anisotropic displacement parameters ($Å^2 x\ 10^3$)for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-phosphaadamantane. The anisotropic displacement factor exponent takes the form: $-2\pi^2[\ h^2 a^{*2} U^{11} + ... + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
P(1)	22(1)	26(1)	25(1)	-9(1)	4(1)	-4(1)
O(1)	21(1)	17(1)	21(1)	2(1)	4(1)	1(1)
O(2)	22(1)	17(1)	18(1)	-1(1)	0(1)	2(1)
O(3)	18(1)	20(1)	20(1)	3(1)	1(1)	-2(1)
C(1)	19(1)	17(1)	21(1)	-1(1)	3(1)	1(1)
C(2)	20(1)	19(1)	19(1)	1(1)	2(1)	3(1)
C(3)	18(1)	20(1)	22(1)	1(1)	1(1)	2(1)
C(4)	18(1)	20(1)	20(1)	0(1)	0(1)	0(1)
C(5)	22(1)	29(1)	25(1)	-2(1)	7(1)	-1(1)
C(6)	27(1)	18(1)	30(1)	0(1)	1(1)	3(1)
C(7)	20(1)	25(1)	32(1)	-1(1)	1(1)	-4(1)
C(8)	16(1)	19(1)	22(1)	0(1)	1(1)	1(1)
C(9)	18(1)	17(1)	21(1)	0(1)	0(1)	0(1)
C(10)	25(1)	27(1)	21(1)	3(1)	0(1)	0(1)

Table I-6. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$x 10^3) for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-phosphaadamantane.

	x	y	z	U(eq)
H(1A)	2630(40)	5340(40)	3291(18)	112(10)
H(3A)	-519	9385	4146	24(4)
H(3B)	-128	9361	3215	22(3)
H(5A)	6024	8924	3075	32(4)
H(5B)	4728	8655	2316	33(4)
H(5C)	5565	7090	2771	41(5)
H(6A)	2593	12540	4127	39(5)
H(6B)	743	12215	4353	36(4)
H(6C)	1155	12306	3427	38(4)
H(7A)	-1547	6543	4196	35(4)
H(7B)	-495	5020	3893	35(4)
H(7C)	-1383	6266	3252	33(4)
H(8A)	4650	6492	4276	25(4)
H(8B)	5303	8342	4444	24(4)
H(10A)	2546	7850	6025	32(4)
H(10B)	4408	8311	5870	29(4)
H(10C)	3778	6443	5757	38(5)

Table I-7. Torsion angles [°] for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-phosphaadamantane.

C(2)-O(1)-C(1)-C(5)	-173.50(9)
C(2)-O(1)-C(1)-C(8)	-52.21(12)
C(2)-O(1)-C(1)-P(1)	66.81(10)
C(4)-P(1)-C(1)-O(1)	-59.65(8)
C(4)-P(1)-C(1)-C(5)	-175.81(9)
C(4)-P(1)-C(1)-C(8)	58.87(8)
C(9)-O(2)-C(2)-O(1)	-60.75(12)
C(9)-O(2)-C(2)-C(6)	-176.11(9)
C(9)-O(2)-C(2)-C(3)	61.77(11)
C(1)-O(1)-C(2)-O(2)	55.95(12)
C(1)-O(1)-C(2)-C(6)	171.88(9)
C(1)-O(1)-C(2)-C(3)	-64.10(12)
O(2)-C(2)-C(3)-C(4)	-58.14(12)
O(1)-C(2)-C(3)-C(4)	63.31(12)
C(6)-C(2)-C(3)-C(4)	-176.56(10)
C(9)-O(3)-C(4)-C(7)	-173.83(9)
C(9)-O(3)-C(4)-C(3)	-52.42(12)
C(9)-O(3)-C(4)-P(1)	65.76(11)
C(2)-C(3)-C(4)-O(3)	52.65(12)
C(2)-C(3)-C(4)-C(7)	169.54(10)
C(2)-C(3)-C(4)-P(1)	-67.30(10)
C(1)-P(1)-C(4)-O(3)	-57.32(8)
C(1)-P(1)-C(4)-C(7)	-174.51(9)
C(1)-P(1)-C(4)-C(3)	61.19(8)
O(1)-C(1)-C(8)-C(9)	52.54(12)
C(5)-C(1)-C(8)-C(9)	169.29(10)
P(1)-C(1)-C(8)-C(9)	-66.33(11)
C(4)-O(3)-C(9)-O(2)	55.95(12)
C(4)-O(3)-C(9)-C(10)	171.64(9)
C(4)-O(3)-C(9)-C(8)	-64.13(12)
C(2)-O(2)-C(9)-O(3)	-60.32(11)
C(2)-O(2)-C(9)-C(10)	-175.53(9)
C(2)-O(2)-C(9)-C(8)	62.37(11)
C(1)-C(8)-C(9)-O(3)	63.51(12)

C(1)-C(8)-C(9)-O(2)	-58.26(12)
C(1)-C(8)-C(9)-C(10)	-176.34(10)

APPENDIX II: Tables of X-Ray Crystallography for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-phenyl-6-phosphaadamantane

Table II-1. Crystal data and structure refinement for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-phenyl-6-phosphaadamantane.

Empirical formula	$C_{16}H_{21}O_3P_1$	
Formula weight	292.30	
Temperature	123(1) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	$P2_1/n$	
Unit cell dimensions	a = 7.8551(6) Å	α= 90°.
	b = 9.1866(7) Å	β= 91.016(3)°.
	c = 20.8860(17) Å	γ = 90°.
Volume	1506.9(2) $Å^3$	
Z	4	
Density (calculated)	1.288 Mg/m^3	
Absorption coefficient	0.187 mm^{-1}	
F(000)	624	
Crystal size	0.65 x 0.38 x 0.10 mm^3	
Theta range for data collection	1.95 to 26.37°.	
Index ranges	-9<=h<=9, -11<=k<=11, -26<=l<=26	
Reflections collected	12542	
Independent reflections	3070 [R_{int} = 0.0201]	
Completeness to theta = 26.37°	99.8 %	
Absorption correction	None	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	3070 / 0 / 206	
Goodness-of-fit on F^2	1.007	
Final R indices [$I > 2\sigma(I)$]	R_1 = 0.0348, wR^2 = 0.0897	
R indices (all data)	R_1 = 0.0378, wR^2 = 0.0918	
Largest diff. peak and hole	0.395 and -0.272 $e.Å^{-3}$	

Table II-2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-phenyl-6-phosphaadamantane. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
P(1)	6927(1)	7829(1)	1811(1)	19(1)
O(1)	8031(1)	10351(1)	1315(1)	20(1)
O(2)	10626(1)	9476(1)	926(1)	20(1)
O(3)	10043(1)	7089(1)	1261(1)	19(1)
C(1)	7076(2)	9081(2)	1099(1)	18(1)
C(2)	9792(2)	10097(2)	1464(1)	20(1)
C(3)	10015(2)	9052(2)	2030(1)	21(1)
C(4)	9290(2)	7556(2)	1858(1)	19(1)
C(5)	5337(2)	9644(2)	894(1)	24(1)
C(6)	10573(2)	11575(2)	1587(1)	25(1)
C(7)	9787(2)	6425(2)	2358(1)	26(1)
C(8)	8031(2)	8375(2)	551(1)	19(1)
C(9)	9886(2)	8106(2)	745(1)	19(1)
C(10)	10934(2)	7510(2)	207(1)	24(1)
C(11)	6033(2)	6166(2)	1456(1)	20(1)
C(12)	4250(2)	6086(2)	1443(1)	23(1)
C(13)	3405(2)	4862(2)	1208(1)	26(1)
C(14)	4335(2)	3675(2)	998(1)	26(1)
C(15)	6102(2)	3722(2)	1017(1)	26(1)
C(16)	6947(2)	4961(2)	1236(1)	23(1)

Table II-3. Selected bond lengths [Å] and angles [°] for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-phenyl-6-phosphaadamantane.

P(1)-C(11)	1.8330(15)
P(1)-C(4)	1.8742(14)
P(1)-C(1)	1.8849(14)
O(1)-C(2)	1.4319(17)
O(1)-C(1)	1.4537(16)
O(2)-C(2)	1.4305(16)
O(2)-C(9)	1.4334(17)
O(3)-C(9)	1.4300(16)
O(3)-C(4)	1.4531(16)
C(1)-C(5)	1.5151(19)
C(1)-C(8)	1.5248(19)
C(2)-C(6)	1.509(2)
C(2)-C(3)	1.529(2)
C(3)-C(4)	1.529(2)
C(4)-C(7)	1.520(2)
C(8)-C(9)	1.5258(19)
C(9)-C(10)	1.5080(19)
C(11)-C(16)	1.401(2)
C(11)-C(12)	1.403(2)
C(12)-C(13)	1.390(2)
C(13)-C(14)	1.389(2)
C(14)-C(15)	1.388(2)
C(15)-C(16)	1.390(2)
C(11)-P(1)-C(4)	106.34(7)
C(11)-P(1)-C(1)	102.61(6)
C(4)-P(1)-C(1)	92.71(6)
C(2)-O(1)-C(1)	115.35(10)
C(2)-O(2)-C(9)	111.61(10)
C(9)-O(3)-C(4)	115.03(10)
O(1)-C(1)-C(5)	105.76(11)
O(1)-C(1)-C(8)	108.43(11)
C(5)-C(1)-C(8)	112.70(12)

O(1)-C(1)-P(1)	106.53(9)
C(5)-C(1)-P(1)	111.24(10)
C(8)-C(1)-P(1)	111.76(9)
O(2)-C(2)-O(1)	110.33(11)
O(2)-C(2)-C(6)	107.59(11)
O(1)-C(2)-C(6)	106.17(12)
O(2)-C(2)-C(3)	108.01(12)
O(1)-C(2)-C(3)	111.53(11)
C(6)-C(2)-C(3)	113.14(12)
C(4)-C(3)-C(2)	110.25(11)
O(3)-C(4)-C(7)	106.55(11)
O(3)-C(4)-C(3)	108.12(11)
C(7)-C(4)-C(3)	111.30(12)
O(3)-C(4)-P(1)	114.36(9)
C(7)-C(4)-P(1)	111.69(10)
C(3)-C(4)-P(1)	104.85(10)
C(1)-C(8)-C(9)	110.46(11)
O(3)-C(9)-O(2)	110.24(10)
O(3)-C(9)-C(10)	106.50(11)
O(2)-C(9)-C(10)	106.92(11)
O(3)-C(9)-C(8)	112.01(11)
O(2)-C(9)-C(8)	107.97(11)
C(10)-C(9)-C(8)	113.09(12)
C(16)-C(11)-C(12)	118.02(13)
C(16)-C(11)-P(1)	126.62(11)
C(12)-C(11)-P(1)	115.25(11)
C(13)-C(12)-C(11)	121.28(14)
C(14)-C(13)-C(12)	119.77(14)
C(15)-C(14)-C(13)	119.82(14)
C(14)-C(15)-C(16)	120.43(14)
C(15)-C(16)-C(11)	120.66(13)

Table II-4. Bond lengths [Å] and angles [°] for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-phenyl-6-phosphaadamantane.

P(1)-C(11)	1.8330(15)
P(1)-C(4)	1.8742(14)
P(1)-C(1)	1.8849(14)
O(1)-C(2)	1.4319(17)
O(1)-C(1)	1.4537(16)
O(2)-C(2)	1.4305(16)
O(2)-C(9)	1.4334(17)
O(3)-C(9)	1.4300(16)
O(3)-C(4)	1.4531(16)
C(1)-C(5)	1.5151(19)
C(1)-C(8)	1.5248(19)
C(2)-C(6)	1.509(2)
C(2)-C(3)	1.529(2)
C(3)-C(4)	1.529(2)
C(4)-C(7)	1.520(2)
C(8)-C(9)	1.5258(19)
C(9)-C(10)	1.5080(19)
C(11)-C(16)	1.401(2)
C(11)-C(12)	1.403(2)
C(12)-C(13)	1.390(2)
C(13)-C(14)	1.389(2)
C(14)-C(15)	1.388(2)
C(15)-C(16)	1.390(2)
C(3)-H(3A)	0.9900
C(3)-H(3B)	0.9900
C(5)-H(5A)	0.9800
C(5)-H(5B)	0.9800
C(5)-H(5C)	0.9800
C(6)-H(6A)	0.9800
C(6)-H(6B)	0.9800
C(6)-H(6C)	0.9800
C(7)-H(7A)	0.9800
C(7)-H(7B)	0.9800

C(7)-H(7C)	0.9800
C(8)-H(8A)	0.9900
C(8)-H(8B)	0.9900
C(10)-H(10A)	0.9800
C(10)-H(10B)	0.9800
C(10)-H(10C)	0.9800
C(12)-H(12A)	0.9500
C(13)-H(13A)	0.9500
C(14)-H(14A)	0.9500
C(15)-H(15A)	0.9500
C(16)-H(16A)	0.9500

C(11)-P(1)-C(4)	106.34(7)
C(11)-P(1)-C(1)	102.61(6)
C(4)-P(1)-C(1)	92.71(6)
C(2)-O(1)-C(1)	115.35(10)
C(2)-O(2)-C(9)	111.61(10)
C(9)-O(3)-C(4)	115.03(10)
O(1)-C(1)-C(5)	105.76(11)
O(1)-C(1)-C(8)	108.43(11)
C(5)-C(1)-C(8)	112.70(12)
O(1)-C(1)-P(1)	106.53(9)
C(5)-C(1)-P(1)	111.24(10)
C(8)-C(1)-P(1)	111.76(9)
O(2)-C(2)-O(1)	110.33(11)
O(2)-C(2)-C(6)	107.59(11)
O(1)-C(2)-C(6)	106.17(12)
O(2)-C(2)-C(3)	108.01(12)
O(1)-C(2)-C(3)	111.53(11)
C(6)-C(2)-C(3)	113.14(12)
C(4)-C(3)-C(2)	110.25(11)
O(3)-C(4)-C(7)	106.55(11)
O(3)-C(4)-C(3)	108.12(11)
C(7)-C(4)-C(3)	111.30(12)
O(3)-C(4)-P(1)	114.36(9)
C(7)-C(4)-P(1)	111.69(10)

C(3)-C(4)-P(1)	104.85(10)
C(1)-C(8)-C(9)	110.46(11)
O(3)-C(9)-O(2)	110.24(10)
O(3)-C(9)-C(10)	106.50(11)
O(2)-C(9)-C(10)	106.92(11)
O(3)-C(9)-C(8)	112.01(11)
O(2)-C(9)-C(8)	107.97(11)
C(10)-C(9)-C(8)	113.09(12)
C(16)-C(11)-C(12)	118.02(13)
C(16)-C(11)-P(1)	126.62(11)
C(12)-C(11)-P(1)	115.25(11)
C(13)-C(12)-C(11)	121.28(14)
C(14)-C(13)-C(12)	119.77(14)
C(15)-C(14)-C(13)	119.82(14)
C(14)-C(15)-C(16)	120.43(14)
C(15)-C(16)-C(11)	120.66(13)
C(4)-C(3)-H(3A)	109.6
C(2)-C(3)-H(3A)	109.6
C(4)-C(3)-H(3B)	109.6
C(2)-C(3)-H(3B)	109.6
H(3A)-C(3)-H(3B)	108.1
C(1)-C(5)-H(5A)	109.5
C(1)-C(5)-H(5B)	109.5
H(5A)-C(5)-H(5B)	109.5
C(1)-C(5)-H(5C)	109.5
H(5A)-C(5)-H(5C)	109.5
H(5B)-C(5)-H(5C)	109.5
C(2)-C(6)-H(6A)	109.5
C(2)-C(6)-H(6B)	109.5
H(6A)-C(6)-H(6B)	109.5
C(2)-C(6)-H(6C)	109.5
H(6A)-C(6)-H(6C)	109.5
H(6B)-C(6)-H(6C)	109.5
C(4)-C(7)-H(7A)	109.5
C(4)-C(7)-H(7B)	109.5
H(7A)-C(7)-H(7B)	109.5

C(4)-C(7)-H(7C)	109.5
H(7A)-C(7)-H(7C)	109.5
H(7B)-C(7)-H(7C)	109.5
C(1)-C(8)-H(8A)	109.6
C(9)-C(8)-H(8A)	109.6
C(1)-C(8)-H(8B)	109.6
C(9)-C(8)-H(8B)	109.6
H(8A)-C(8)-H(8B)	108.1
C(9)-C(10)-H(10A)	109.5
C(9)-C(10)-H(10B)	109.5
H(10A)-C(10)-H(10B)	109.5
C(9)-C(10)-H(10C)	109.5
H(10A)-C(10)-H(10C)	109.5
H(10B)-C(10)-H(10C)	109.5
C(13)-C(12)-H(12A)	119.4
C(11)-C(12)-H(12A)	119.4
C(14)-C(13)-H(13A)	120.1
C(12)-C(13)-H(13A)	120.1
C(15)-C(14)-H(14A)	120.1
C(13)-C(14)-H(14A)	120.1
C(14)-C(15)-H(15A)	119.8
C(16)-C(15)-H(15A)	119.8
C(15)-C(16)-H(16A)	119.7
C(11)-C(16)-H(16A)	119.7

Table II-5. Anisotropic displacement parameters ($Å^2 x\ 10^3$)for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-phenyl-6-phosphaadamantane. The anisotropic displacement factor exponent takes the form: $-2\pi^2[\ h^2 a^{*2} U^{11} + ... + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
P(1)	18(1)	19(1)	18(1)	-1(1)	3(1)	0(1)
O(1)	20(1)	17(1)	23(1)	-2(1)	-1(1)	-1(1)
O(2)	21(1)	22(1)	18(1)	-1(1)	3(1)	-3(1)
O(3)	19(1)	21(1)	16(1)	2(1)	3(1)	3(1)
C(1)	20(1)	16(1)	20(1)	0(1)	-1(1)	-1(1)
C(2)	19(1)	23(1)	17(1)	-2(1)	1(1)	-2(1)
C(3)	20(1)	26(1)	17(1)	-1(1)	-1(1)	-2(1)
C(4)	19(1)	24(1)	15(1)	0(1)	2(1)	0(1)
C(5)	21(1)	21(1)	30(1)	0(1)	-4(1)	2(1)
C(6)	27(1)	25(1)	24(1)	-2(1)	0(1)	-7(1)
C(7)	27(1)	30(1)	21(1)	6(1)	0(1)	2(1)
C(8)	23(1)	19(1)	16(1)	1(1)	-1(1)	0(1)
C(9)	22(1)	19(1)	16(1)	1(1)	2(1)	-1(1)
C(10)	26(1)	26(1)	19(1)	-1(1)	5(1)	0(1)
C(11)	22(1)	19(1)	18(1)	2(1)	3(1)	-1(1)
C(12)	22(1)	20(1)	28(1)	2(1)	4(1)	2(1)
C(13)	21(1)	24(1)	33(1)	2(1)	0(1)	0(1)
C(14)	29(1)	21(1)	29(1)	-1(1)	2(1)	-4(1)
C(15)	29(1)	20(1)	29(1)	-2(1)	8(1)	2(1)
C(16)	20(1)	22(1)	27(1)	0(1)	6(1)	0(1)

Table II-6. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$x 10^3) for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-phenyl-6-phosphaadamantane.

	x	y	z	U(eq)
H(3A)	11239	8960	2143	27(4)
H(3B)	9420	9445	2406	22(4)
H(5A)	5466	10386	562	31(5)
H(5B)	4772	10072	1264	32(5)
H(5C)	4649	8837	725	34(5)
H(6A)	10445	12177	1202	34(5)
H(6B)	11785	11462	1694	28(5)
H(6C)	9995	12045	1944	29(5)
H(7A)	11031	6343	2384	33(5)
H(7B)	9297	5481	2238	33(5)
H(7C)	9356	6721	2776	34(5)
H(8A)	7979	9018	171	23(4)
H(8B)	7481	7439	435	23(4)
H(10A)	12102	7338	361	28(5)
H(10B)	10944	8213	-146	34(5)
H(10C)	10436	6591	55	34(5)
H(12A)	3606	6883	1597	24(4)
H(13A)	2196	4838	1192	31(5)
H(14A)	3764	2832	841	34(5)
H(15A)	6738	2904	880	35(5)
H(16A)	8156	4991	1236	27(4)

Table II-7. Torsion angles [°] for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-phenyl-6-phosphaadamantane.

C(2)-O(1)-C(1)-C(5)	-173.17(11)
C(2)-O(1)-C(1)-C(8)	-52.06(14)
C(2)-O(1)-C(1)-P(1)	68.37(12)
C(11)-P(1)-C(1)-O(1)	-170.91(9)
C(4)-P(1)-C(1)-O(1)	-63.50(9)
C(11)-P(1)-C(1)-C(5)	74.29(11)
C(4)-P(1)-C(1)-C(5)	-178.29(10)
C(11)-P(1)-C(1)-C(8)	-52.64(11)
C(4)-P(1)-C(1)-C(8)	54.77(10)
C(9)-O(2)-C(2)-O(1)	-60.60(14)
C(9)-O(2)-C(2)-C(6)	-176.00(11)
C(9)-O(2)-C(2)-C(3)	61.54(13)
C(1)-O(1)-C(2)-O(2)	56.17(14)
C(1)-O(1)-C(2)-C(6)	172.46(11)
C(1)-O(1)-C(2)-C(3)	-63.88(14)
O(2)-C(2)-C(3)-C(4)	-57.67(14)
O(1)-C(2)-C(3)-C(4)	63.73(15)
C(6)-C(2)-C(3)-C(4)	-176.66(12)
C(9)-O(3)-C(4)-C(7)	-172.97(11)
C(9)-O(3)-C(4)-C(3)	-53.24(14)
C(9)-O(3)-C(4)-P(1)	63.13(13)
C(2)-C(3)-C(4)-O(3)	52.55(14)
C(2)-C(3)-C(4)-C(7)	169.25(12)
C(2)-C(3)-C(4)-P(1)	-69.84(12)
C(11)-P(1)-C(4)-O(3)	50.99(11)
C(1)-P(1)-C(4)-O(3)	-52.99(11)
C(11)-P(1)-C(4)-C(7)	-70.12(11)
C(1)-P(1)-C(4)-C(7)	-174.10(11)
C(11)-P(1)-C(4)-C(3)	169.23(9)
C(1)-P(1)-C(4)-C(3)	65.25(9)
O(1)-C(1)-C(8)-C(9)	51.93(14)
C(5)-C(1)-C(8)-C(9)	168.66(12)
P(1)-C(1)-C(8)-C(9)	-65.19(13)
C(4)-O(3)-C(9)-O(2)	57.12(14)

C(4)-O(3)-C(9)-C(10)	172.77(11)
C(4)-O(3)-C(9)-C(8)	-63.12(14)
C(2)-O(2)-C(9)-O(3)	-60.83(14)
C(2)-O(2)-C(9)-C(10)	-176.21(11)
C(2)-O(2)-C(9)-C(8)	61.82(13)
C(1)-C(8)-C(9)-O(3)	63.88(15)
C(1)-C(8)-C(9)-O(2)	-57.67(14)
C(1)-C(8)-C(9)-C(10)	-175.76(12)
C(4)-P(1)-C(11)-C(16)	-2.72(15)
C(1)-P(1)-C(11)-C(16)	93.94(13)
C(4)-P(1)-C(11)-C(12)	173.35(11)
C(1)-P(1)-C(11)-C(12)	-89.98(12)
C(16)-C(11)-C(12)-C(13)	-1.2(2)
P(1)-C(11)-C(12)-C(13)	-177.61(12)
C(11)-C(12)-C(13)-C(14)	1.8(2)
C(12)-C(13)-C(14)-C(15)	-0.7(2)
C(13)-C(14)-C(15)-C(16)	-1.1(2)
C(14)-C(15)-C(16)-C(11)	1.7(2)
C(12)-C(11)-C(16)-C(15)	-0.5(2)
P(1)-C(11)-C(16)-C(15)	175.43(12)

APPENDIX III: Tables of X-Ray Crystallography for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-(*o*-tolyl)-6-phosphaadamantane

Table III-1. Crystal data and structure refinement for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-(*o*-tolyl)-6-phosphaadamantane.

Identification code	csf158s	
Empirical formula	$C_{17}H_{23}O_3P_1$	
Formula weight	306.32	
Temperature	123(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	$P2_1/n$	
Unit cell dimensions	a = 7.4988(6) Å	α= 90°.
	b = 28.084(2) Å	β= 110.827(2)°.
	c = 8.2246(6) Å	γ = 90°.
Volume	1618.9(2) $Å^3$	
Z	4	
Density (calculated)	1.257 Mg/m^3	
Absorption coefficient	0.177 mm^{-1}	
F(000)	656	
Crystal size	0.35 x 0.35 x 0.22 mm^3	
Theta range for data collection	1.45 to 26.37°.	
Index ranges	-9<=h<=9, -34<=k<=35, -10<=l<=10	
Reflections collected	13761	
Independent reflections	3312 [R(int) = 0.0143]	
Completeness to theta = 26.37°	99.8 %	
Absorption correction	None	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	3312 / 0 / 218	
Goodness-of-fit on F^2	1.005	
Final R indices [I>2sigma(I)]	R1 = 0.0336, wR2 = 0.0975	
R indices (all data)	R1 = 0.0348, wR2 = 0.0986	
Largest diff. peak and hole	0.258 and -0.259 $e.Å^{-3}$	

Table III-2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-(*o*-tolyl)-6-phosphaadamantane. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
P(1)	7554(1)	1586(1)	8619(1)	21(1)
O(1)	8744(1)	916(1)	11078(1)	22(1)
O(2)	7337(1)	259(1)	9341(1)	22(1)
O(3)	6178(1)	727(1)	6809(1)	22(1)
C(1)	9404(2)	1126(1)	9777(2)	21(1)
C(2)	7056(2)	633(1)	10402(2)	22(1)
C(3)	5330(2)	925(1)	9292(2)	24(1)
C(4)	5660(2)	1124(1)	7684(2)	22(1)
C(5)	11305(2)	1359(1)	10784(2)	26(1)
C(6)	6775(2)	406(1)	11962(2)	29(1)
C(7)	3851(2)	1333(1)	6375(2)	30(1)
C(8)	9584(2)	730(1)	8577(2)	21(1)
C(9)	7737(2)	443(1)	7875(2)	21(1)
C(10)	7851(2)	21(1)	6785(2)	26(1)
C(11)	8320(2)	1797(1)	6856(2)	21(1)
C(12)	8068(2)	1540(1)	5330(2)	24(1)
C(13)	8603(2)	1728(1)	4007(2)	28(1)
C(14)	9410(2)	2179(1)	4199(2)	29(1)
C(15)	9680(2)	2438(1)	5704(2)	28(1)
C(16)	9131(2)	2257(1)	7042(2)	23(1)
C(17)	9409(2)	2565(1)	8620(2)	29(1)

Table III-3. Bond lengths [Å] and angles [°] for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-(*o*-tolyl)-6-phosphaadamantane.

P(1)-C(11)	1.8370(13)
P(1)-C(4)	1.8764(13)
P(1)-C(1)	1.8877(13)
O(1)-C(2)	1.4305(15)
O(1)-C(1)	1.4539(14)
O(2)-C(2)	1.4277(15)
O(2)-C(9)	1.4381(15)
O(3)-C(9)	1.4288(15)
O(3)-C(4)	1.4513(15)
C(1)-C(5)	1.5189(17)
C(1)-C(8)	1.5237(17)
C(2)-C(6)	1.5129(17)
C(2)-C(3)	1.5304(18)
C(3)-C(4)	1.5340(18)
C(3)-H(3A)	0.9900
C(3)-H(3B)	0.9900
C(4)-C(7)	1.5185(18)
C(5)-H(5A)	0.9800
C(5)-H(5B)	0.9800
C(5)-H(5C)	0.9800
C(6)-H(6A)	0.9800
C(6)-H(6B)	0.9800
C(6)-H(6C)	0.9800
C(7)-H(7A)	0.9800
C(7)-H(7B)	0.9800
C(7)-H(7C)	0.9800
C(8)-C(9)	1.5268(17)
C(8)-H(8A)	0.9900
C(8)-H(8B)	0.9900
C(9)-C(10)	1.5074(18)
C(10)-H(10A)	0.9800
C(10)-H(10B)	0.9800
C(10)-H(10C)	0.9800

C(11)-C(12)	1.4019(18)
C(11)-C(16)	1.4131(18)
C(12)-C(13)	1.3904(19)
C(12)-H(12A)	0.9500
C(13)-C(14)	1.390(2)
C(13)-H(13A)	0.9500
C(14)-C(15)	1.386(2)
C(14)-H(14A)	0.9500
C(15)-C(16)	1.3996(19)
C(15)-H(15A)	0.9500
C(16)-C(17)	1.5103(18)
C(17)-H(17A)	0.9800
C(17)-H(17B)	0.9800
C(17)-H(17C)	0.9800

C(11)-P(1)-C(4)	107.67(6)
C(11)-P(1)-C(1)	103.84(5)
C(4)-P(1)-C(1)	92.62(6)
C(2)-O(1)-C(1)	115.18(9)
C(2)-O(2)-C(9)	111.63(9)
C(9)-O(3)-C(4)	115.38(9)
O(1)-C(1)-C(5)	105.77(10)
O(1)-C(1)-C(8)	108.23(10)
C(5)-C(1)-C(8)	112.70(10)
O(1)-C(1)-P(1)	105.49(8)
C(5)-C(1)-P(1)	111.04(9)
C(8)-C(1)-P(1)	113.05(8)
O(2)-C(2)-O(1)	110.12(10)
O(2)-C(2)-C(6)	107.72(11)
O(1)-C(2)-C(6)	106.03(10)
O(2)-C(2)-C(3)	107.85(10)
O(1)-C(2)-C(3)	112.14(11)
C(6)-C(2)-C(3)	112.91(11)
C(2)-C(3)-C(4)	110.38(10)
C(2)-C(3)-H(3A)	109.6
C(4)-C(3)-H(3A)	109.6

C(2)-C(3)-H(3B)	109.6
C(4)-C(3)-H(3B)	109.6
H(3A)-C(3)-H(3B)	108.1
O(3)-C(4)-C(7)	105.90(10)
O(3)-C(4)-C(3)	107.57(10)
C(7)-C(4)-C(3)	112.01(11)
O(3)-C(4)-P(1)	115.95(8)
C(7)-C(4)-P(1)	112.20(9)
C(3)-C(4)-P(1)	103.26(9)
C(1)-C(5)-H(5A)	109.5
C(1)-C(5)-H(5B)	109.5
H(5A)-C(5)-H(5B)	109.5
C(1)-C(5)-H(5C)	109.5
H(5A)-C(5)-H(5C)	109.5
H(5B)-C(5)-H(5C)	109.5
C(2)-C(6)-H(6A)	109.5
C(2)-C(6)-H(6B)	109.5
H(6A)-C(6)-H(6B)	109.5
C(2)-C(6)-H(6C)	109.5
H(6A)-C(6)-H(6C)	109.5
H(6B)-C(6)-H(6C)	109.5
C(4)-C(7)-H(7A)	109.5
C(4)-C(7)-H(7B)	109.5
H(7A)-C(7)-H(7B)	109.5
C(4)-C(7)-H(7C)	109.5
H(7A)-C(7)-H(7C)	109.5
H(7B)-C(7)-H(7C)	109.5
C(1)-C(8)-C(9)	110.66(10)
C(1)-C(8)-H(8A)	109.5
C(9)-C(8)-H(8A)	109.5
C(1)-C(8)-H(8B)	109.5
C(9)-C(8)-H(8B)	109.5
H(8A)-C(8)-H(8B)	108.1
O(3)-C(9)-O(2)	110.22(10)
O(3)-C(9)-C(10)	106.34(10)
O(2)-C(9)-C(10)	106.76(10)

O(3)-C(9)-C(8)	111.86(10)
O(2)-C(9)-C(8)	107.69(10)
C(10)-C(9)-C(8)	113.85(11)
C(9)-C(10)-H(10A)	109.5
C(9)-C(10)-H(10B)	109.5
H(10A)-C(10)-H(10B)	109.5
C(9)-C(10)-H(10C)	109.5
H(10A)-C(10)-H(10C)	109.5
H(10B)-C(10)-H(10C)	109.5
C(12)-C(11)-C(16)	118.95(12)
C(12)-C(11)-P(1)	124.04(10)
C(16)-C(11)-P(1)	116.94(10)
C(13)-C(12)-C(11)	121.35(13)
C(13)-C(12)-H(12A)	119.3
C(11)-C(12)-H(12A)	119.3
C(14)-C(13)-C(12)	119.52(13)
C(14)-C(13)-H(13A)	120.2
C(12)-C(13)-H(13A)	120.2
C(15)-C(14)-C(13)	119.89(13)
C(15)-C(14)-H(14A)	120.1
C(13)-C(14)-H(14A)	120.1
C(14)-C(15)-C(16)	121.48(13)
C(14)-C(15)-H(15A)	119.3
C(16)-C(15)-H(15A)	119.3
C(15)-C(16)-C(11)	118.80(12)
C(15)-C(16)-C(17)	118.66(12)
C(11)-C(16)-C(17)	122.54(12)
C(16)-C(17)-H(17A)	109.5
C(16)-C(17)-H(17B)	109.5
H(17A)-C(17)-H(17B)	109.5
C(16)-C(17)-H(17C)	109.5
H(17A)-C(17)-H(17C)	109.5
H(17B)-C(17)-H(17C)	109.5

Symmetry transformations used to generate equivalent atoms:

Table III-4. Anisotropic displacement parameters ($Å^2 x\ 10^3$) for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-(*o*-tolyl)-6-phosphaadamantane. The anisotropic displacement factor exponent takes the form: $-2\pi^2[\ h^2 a^{*2} U^{11} + ... + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
P(1)	21(1)	20(1)	23(1)	-2(1)	10(1)	0(1)
O(1)	22(1)	28(1)	19(1)	-1(1)	10(1)	-3(1)
O(2)	27(1)	21(1)	21(1)	1(1)	11(1)	0(1)
O(3)	22(1)	21(1)	21(1)	-1(1)	5(1)	2(1)
C(1)	20(1)	24(1)	20(1)	1(1)	10(1)	0(1)
C(2)	23(1)	24(1)	23(1)	-2(1)	11(1)	-3(1)
C(3)	20(1)	25(1)	29(1)	-1(1)	13(1)	-1(1)
C(4)	19(1)	22(1)	26(1)	-1(1)	9(1)	1(1)
C(5)	21(1)	34(1)	25(1)	-2(1)	8(1)	-4(1)
C(6)	33(1)	32(1)	26(1)	0(1)	16(1)	-5(1)
C(7)	22(1)	30(1)	36(1)	4(1)	7(1)	4(1)
C(8)	20(1)	23(1)	20(1)	2(1)	9(1)	2(1)
C(9)	24(1)	21(1)	19(1)	3(1)	9(1)	3(1)
C(10)	35(1)	22(1)	24(1)	0(1)	12(1)	2(1)
C(11)	19(1)	21(1)	23(1)	1(1)	8(1)	2(1)
C(12)	26(1)	22(1)	25(1)	0(1)	11(1)	2(1)
C(13)	29(1)	31(1)	24(1)	0(1)	11(1)	4(1)
C(14)	28(1)	34(1)	30(1)	5(1)	15(1)	1(1)
C(15)	25(1)	26(1)	35(1)	2(1)	12(1)	-3(1)
C(16)	19(1)	23(1)	28(1)	-1(1)	9(1)	0(1)
C(17)	28(1)	26(1)	35(1)	-8(1)	13(1)	-7(1)

Table III-5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$x 10^3) for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-(*o*-tolyl)-6-phosphaadamantane.

	x	y	z	U(eq)
H(3A)	5117	1191	9991	25(4)
H(3B)	4177	722	8920	32(4)
H(5A)	12215	1115	11435	39(5)
H(5B)	11129	1593	11597	37(5)
H(5C)	11799	1518	9972	34(4)
H(6A)	7881	206	12580	41(5)
H(6B)	5621	209	11572	37(5)
H(6C)	6641	655	12745	46(5)
H(7A)	2868	1085	5995	42(5)
H(7B)	4120	1454	5368	37(5)
H(7C)	3399	1594	6917	38(5)
H(8A)	10649	516	9225	24(4)
H(8B)	9874	870	7595	27(4)
H(10A)	6608	-138	6341	35(5)
H(10B)	8816	-202	7499	36(5)
H(10C)	8202	129	5806	40(5)
H(12A)	7520	1231	5196	27(4)
H(13A)	8419	1549	2980	30(4)
H(14A)	9777	2311	3300	36(4)
H(15A)	10250	2744	5829	39(5)
H(17A)	9784	2886	8406	57(6)
H(17B)	10410	2427	9630	52(6)
H(17C)	8212	2580	8846	45(5)

Table III-6. Torsion angles [°] for 1,3,5,7-tetramethyl-2,4,8-trioxa-6-(*o*-tolyl)-6-phosphaadamantane.

C(2)-O(1)-C(1)-C(5)	-173.67(10)
C(2)-O(1)-C(1)-C(8)	-52.66(13)
C(2)-O(1)-C(1)-P(1)	68.60(11)
C(11)-P(1)-C(1)-O(1)	-174.55(8)
C(4)-P(1)-C(1)-O(1)	-65.63(8)
C(11)-P(1)-C(1)-C(5)	71.33(9)
C(4)-P(1)-C(1)-C(5)	-179.75(9)
C(11)-P(1)-C(1)-C(8)	-56.47(10)
C(4)-P(1)-C(1)-C(8)	52.45(9)
C(9)-O(2)-C(2)-O(1)	-61.16(12)
C(9)-O(2)-C(2)-C(6)	-176.35(10)
C(9)-O(2)-C(2)-C(3)	61.50(13)
C(1)-O(1)-C(2)-O(2)	57.04(13)
C(1)-O(1)-C(2)-C(6)	173.30(10)
C(1)-O(1)-C(2)-C(3)	-63.05(13)
O(2)-C(2)-C(3)-C(4)	-58.15(13)
O(1)-C(2)-C(3)-C(4)	63.26(13)
C(6)-C(2)-C(3)-C(4)	-177.04(11)
C(9)-O(3)-C(4)-C(7)	-173.36(10)
C(9)-O(3)-C(4)-C(3)	-53.43(13)
C(9)-O(3)-C(4)-P(1)	61.50(12)
C(2)-C(3)-C(4)-O(3)	52.90(13)
C(2)-C(3)-C(4)-C(7)	168.88(11)
C(2)-C(3)-C(4)-P(1)	-70.20(11)
C(11)-P(1)-C(4)-O(3)	55.09(10)
C(1)-P(1)-C(4)-O(3)	-50.33(10)
C(11)-P(1)-C(4)-C(7)	-66.75(11)
C(1)-P(1)-C(4)-C(7)	-172.17(10)
C(11)-P(1)-C(4)-C(3)	172.45(8)
C(1)-P(1)-C(4)-C(3)	67.03(8)
O(1)-C(1)-C(8)-C(9)	52.12(13)
C(5)-C(1)-C(8)-C(9)	168.72(10)
P(1)-C(1)-C(8)-C(9)	-64.35(12)
C(4)-O(3)-C(9)-O(2)	57.13(13)

C(4)-O(3)-C(9)-C(10)	172.49(10)
C(4)-O(3)-C(9)-C(8)	-62.65(13)
C(2)-O(2)-C(9)-O(3)	-60.55(13)
C(2)-O(2)-C(9)-C(10)	-175.64(10)
C(2)-O(2)-C(9)-C(8)	61.72(12)
C(1)-C(8)-C(9)-O(3)	63.85(13)
C(1)-C(8)-C(9)-O(2)	-57.41(13)
C(1)-C(8)-C(9)-C(10)	-175.56(10)
C(4)-P(1)-C(11)-C(12)	-21.33(13)
C(1)-P(1)-C(11)-C(12)	76.01(12)
C(4)-P(1)-C(11)-C(16)	155.69(10)
C(1)-P(1)-C(11)-C(16)	-106.96(10)
C(16)-C(11)-C(12)-C(13)	0.18(19)
P(1)-C(11)-C(12)-C(13)	177.14(10)
C(11)-C(12)-C(13)-C(14)	0.2(2)
C(12)-C(13)-C(14)-C(15)	0.2(2)
C(13)-C(14)-C(15)-C(16)	-0.9(2)
C(14)-C(15)-C(16)-C(11)	1.3(2)
C(14)-C(15)-C(16)-C(17)	-178.03(13)
C(12)-C(11)-C(16)-C(15)	-0.87(19)
P(1)-C(11)-C(16)-C(15)	-178.05(10)
C(12)-C(11)-C(16)-C(17)	178.39(12)
P(1)-C(11)-C(16)-C(17)	1.21(17)

Symmetry transformations used to generate equivalent atoms.

APPENDIX IV: Tables of X-Ray Crystallography for $Pd(PA\text{-}Ph)_2O_2$

Table IV-1. Crystal data and structure refinement for $Pd(PA\text{-}Ph)_2O_2$.

Identification code	s92	
Empirical formula	$C_{32}\ H_{42}\ O_8\ P_2\ Pd_1$	
Formula weight	723.00	
Temperature	120(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	C2/c	
Unit cell dimensions	a = 14.9474(4) Å	α= 90°.
	b = 16.3496(4) Å	β= 118.0140(10)°.
	c = 14.9797(4) Å	γ = 90°.
Volume	3231.87(15) $Å^3$	
Z	4	
Density (calculated)	1.486 Mg/m^3	
Absorption coefficient	0.722 mm^{-1}	
F(000)	1496	
Crystal size	0.38 x 0.04 x 0.03 mm^3	
Theta range for data collection	2.92 to 26.37°.	
Index ranges	-18<=h<=18, -20<=k<=20, -18<=l<=18	
Reflections collected	21668	
Independent reflections	3304 [R(int) = 0.0697]	
Completeness to theta = 26.37°	99.8 %	
Absorption correction	None	
Max. and min. transmission	0.9787 and 0.7710	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	3304 / 0 / 204	
Goodness-of-fit on F^2	1.010	
Final R indices [I>2sigma(I)]	R1 = 0.0331, wR2 = 0.0760	
R indices (all data)	R1 = 0.0412, wR2 = 0.0799	
Largest diff. peak and hole	0.611 and -0.737 $e.Å^{-3}$	

Table IV-2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for $Pd(PA\text{-}Ph)_2O_2$. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
Pd(1)	0	2711(1)	2500	13(1)
P(1)	1089(1)	1897(1)	2180(1)	13(1)
O(1)	1029(1)	2903(1)	728(1)	17(1)
O(2)	1181(1)	1873(1)	-296(1)	19(1)
O(3)	1293(1)	847(1)	850(1)	17(1)
O(4)	408(1)	3865(1)	2386(1)	21(1)
C(1)	1794(2)	2538(2)	1657(2)	16(1)
C(2)	493(2)	2340(2)	-90(2)	18(1)
C(3)	-155(2)	1749(2)	153(2)	17(1)
C(4)	518(2)	1206(2)	1050(2)	16(1)
C(5)	2363(2)	3238(2)	2362(2)	19(1)
C(6)	-110(2)	2856(2)	-1021(2)	23(1)
C(7)	-42(2)	494(2)	1206(2)	19(1)
C(8)	2480(2)	1997(2)	1414(2)	16(1)
C(9)	1854(2)	1401(2)	562(2)	18(1)
C(10)	2485(2)	882(2)	246(2)	23(1)
C(11)	2088(2)	1329(2)	3226(2)	15(1)
C(12)	2596(2)	636(2)	3128(2)	18(1)
C(13)	3402(2)	295(2)	3975(2)	23(1)
C(14)	3716(2)	626(2)	4925(2)	23(1)
C(15)	3200(2)	1292(2)	5043(2)	22(1)
C(16)	2395(2)	1640(2)	4200(2)	18(1)
O(5)	5000	600(12)	2500	36(7)

Table IV-3. Bond lengths [Å] and angles [°] for $Pd(PA\text{-}Ph)_2O_2$.

Pd(1)-O(4)#1	2.0148(18)
Pd(1)-O(4)	2.0148(18)
Pd(1)-P(1)#1	2.3206(6)
Pd(1)-P(1)	2.3206(6)
P(1)-C(11)	1.830(2)
P(1)-C(4)	1.874(2)
P(1)-C(1)	1.897(3)
O(1)-C(2)	1.437(3)
O(1)-C(1)	1.452(3)
O(2)-C(2)	1.425(3)
O(2)-C(9)	1.430(3)
O(3)-C(9)	1.433(3)
O(3)-C(4)	1.449(3)
O(4)-O(4)#1	1.413(4)
C(1)-C(5)	1.518(3)
C(1)-C(8)	1.522(4)
C(2)-C(6)	1.513(4)
C(2)-C(3)	1.528(4)
C(3)-C(4)	1.530(3)
C(3)-H(3A)	0.9900
C(3)-H(3B)	0.9900
C(4)-C(7)	1.514(3)
C(5)-H(5A)	0.9800
C(5)-H(5B)	0.9800
C(5)-H(5C)	0.9800
C(6)-H(6A)	0.9800
C(6)-H(6B)	0.9800
C(6)-H(6C)	0.9800
C(7)-H(7A)	0.9800
C(7)-H(7B)	0.9800
C(7)-H(7C)	0.9800
C(8)-C(9)	1.526(3)
C(8)-H(8A)	0.9900
C(8)-H(8B)	0.9900

C(9)-C(10)	1.501(4)
C(10)-H(10A)	0.9800
C(10)-H(10B)	0.9800
C(10)-H(10C)	0.9800
C(11)-C(16)	1.402(3)
C(11)-C(12)	1.410(4)
C(12)-C(13)	1.392(4)
C(12)-H(12A)	0.9500
C(13)-C(14)	1.383(4)
C(13)-H(13A)	0.9500
C(14)-C(15)	1.392(4)
C(14)-H(14A)	0.9500
C(15)-C(16)	1.393(4)
C(15)-H(15A)	0.9500
C(16)-H(16A)	0.9500

O(4)#1-Pd(1)-O(4)	41.05(10)
O(4)#1-Pd(1)-P(1)#1	104.48(5)
O(4)-Pd(1)-P(1)#1	145.53(5)
O(4)#1-Pd(1)-P(1)	145.53(5)
O(4)-Pd(1)-P(1)	104.48(5)
P(1)#1-Pd(1)-P(1)	109.99(3)
C(11)-P(1)-C(4)	108.08(11)
C(11)-P(1)-C(1)	104.20(11)
C(4)-P(1)-C(1)	93.79(11)
C(11)-P(1)-Pd(1)	118.89(8)
C(4)-P(1)-Pd(1)	117.81(8)
C(1)-P(1)-Pd(1)	110.36(8)
C(2)-O(1)-C(1)	115.23(19)
C(2)-O(2)-C(9)	111.68(18)
C(9)-O(3)-C(4)	116.39(19)
O(4)#1-O(4)-Pd(1)	69.48(5)
O(1)-C(1)-C(5)	106.8(2)
O(1)-C(1)-C(8)	108.95(19)
C(5)-C(1)-C(8)	112.6(2)
O(1)-C(1)-P(1)	106.43(16)

C(5)-C(1)-P(1)	111.58(18)
C(8)-C(1)-P(1)	110.22(17)
O(2)-C(2)-O(1)	111.0(2)
O(2)-C(2)-C(6)	106.1(2)
O(1)-C(2)-C(6)	106.3(2)
O(2)-C(2)-C(3)	108.3(2)
O(1)-C(2)-C(3)	111.3(2)
C(6)-C(2)-C(3)	113.7(2)
C(2)-C(3)-C(4)	110.4(2)
C(2)-C(3)-H(3A)	109.6
C(4)-C(3)-H(3A)	109.6
C(2)-C(3)-H(3B)	109.6
C(4)-C(3)-H(3B)	109.6
H(3A)-C(3)-H(3B)	108.1
O(3)-C(4)-C(7)	105.9(2)
O(3)-C(4)-C(3)	108.22(19)
C(7)-C(4)-C(3)	113.5(2)
O(3)-C(4)-P(1)	111.20(16)
C(7)-C(4)-P(1)	112.00(17)
C(3)-C(4)-P(1)	106.02(17)
C(1)-C(5)-H(5A)	109.5
C(1)-C(5)-H(5B)	109.5
H(5A)-C(5)-H(5B)	109.5
C(1)-C(5)-H(5C)	109.5
H(5A)-C(5)-H(5C)	109.5
H(5B)-C(5)-H(5C)	109.5
C(2)-C(6)-H(6A)	109.5
C(2)-C(6)-H(6B)	109.5
H(6A)-C(6)-H(6B)	109.5
C(2)-C(6)-H(6C)	109.5
H(6A)-C(6)-H(6C)	109.5
H(6B)-C(6)-H(6C)	109.5
C(4)-C(7)-H(7A)	109.5
C(4)-C(7)-H(7B)	109.5
H(7A)-C(7)-H(7B)	109.5
C(4)-C(7)-H(7C)	109.5

H(7A)-C(7)-H(7C)	109.5
H(7B)-C(7)-H(7C)	109.5
C(1)-C(8)-C(9)	110.7(2)
C(1)-C(8)-H(8A)	109.5
C(9)-C(8)-H(8A)	109.5
C(1)-C(8)-H(8B)	109.5
C(9)-C(8)-H(8B)	109.5
H(8A)-C(8)-H(8B)	108.1
O(2)-C(9)-O(3)	110.3(2)
O(2)-C(9)-C(10)	107.6(2)
O(3)-C(9)-C(10)	106.3(2)
O(2)-C(9)-C(8)	107.6(2)
O(3)-C(9)-C(8)	111.6(2)
C(10)-C(9)-C(8)	113.3(2)
C(9)-C(10)-H(10A)	109.5
C(9)-C(10)-H(10B)	109.5
H(10A)-C(10)-H(10B)	109.5
C(9)-C(10)-H(10C)	109.5
H(10A)-C(10)-H(10C)	109.5
H(10B)-C(10)-H(10C)	109.5
C(16)-C(11)-C(12)	118.1(2)
C(16)-C(11)-P(1)	116.39(19)
C(12)-C(11)-P(1)	125.48(19)
C(13)-C(12)-C(11)	120.3(2)
C(13)-C(12)-H(12A)	119.8
C(11)-C(12)-H(12A)	119.8
C(14)-C(13)-C(12)	120.7(3)
C(14)-C(13)-H(13A)	119.6
C(12)-C(13)-H(13A)	119.6
C(13)-C(14)-C(15)	119.8(3)
C(13)-C(14)-H(14A)	120.1
C(15)-C(14)-H(14A)	120.1
C(14)-C(15)-C(16)	119.9(2)
C(14)-C(15)-H(15A)	120.1
C(16)-C(15)-H(15A)	120.1
C(15)-C(16)-C(11)	121.1(2)

C(15)-C(16)-H(16A)	119.4
C(11)-C(16)-H(16A)	119.4

Symmetry transformations used to generate equivalent atoms:

#1 -x,y,-z+1/2

Table IV- 4. Anisotropic displacement parameters ($Å^2 x\ 10^3$) for $Pd(PA\text{-}Ph)_2O_2$. The anisotropic displacement factor exponent takes the form: $-2\pi^2[\ h^2\ a^{*2}U^{11} + ... + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
Pd(1)	12(1)	14(1)	11(1)	0	5(1)	0
P(1)	12(1)	15(1)	12(1)	-1(1)	5(1)	-1(1)
O(1)	15(1)	20(1)	13(1)	2(1)	5(1)	1(1)
O(2)	16(1)	28(1)	15(1)	0(1)	9(1)	2(1)
O(3)	14(1)	19(1)	19(1)	-4(1)	10(1)	-1(1)
O(4)	21(1)	16(1)	31(1)	0(1)	15(1)	0(1)
C(1)	13(1)	19(1)	14(1)	2(1)	6(1)	1(1)
C(2)	14(1)	24(1)	14(1)	-1(1)	6(1)	1(1)
C(3)	13(1)	25(1)	13(1)	-4(1)	5(1)	-1(1)
C(4)	14(1)	20(1)	15(1)	-4(1)	8(1)	-2(1)
C(5)	18(1)	19(1)	20(1)	-1(1)	8(1)	-3(1)
C(6)	17(1)	33(2)	18(1)	4(1)	6(1)	1(1)
C(7)	16(1)	20(1)	21(1)	-3(1)	10(1)	-3(1)
C(8)	11(1)	20(1)	16(1)	-1(1)	7(1)	-1(1)
C(9)	15(1)	22(1)	17(1)	-1(1)	8(1)	1(1)
C(10)	19(1)	28(2)	23(1)	-5(1)	12(1)	1(1)
C(11)	12(1)	17(1)	14(1)	1(1)	4(1)	-2(1)
C(12)	18(1)	18(1)	20(1)	-2(1)	10(1)	-3(1)
C(13)	17(1)	18(1)	30(2)	6(1)	9(1)	1(1)
C(14)	15(1)	27(2)	23(1)	8(1)	6(1)	-1(1)
C(15)	21(1)	25(1)	18(1)	0(1)	7(1)	-6(1)
C(16)	16(1)	20(1)	19(1)	0(1)	9(1)	-1(1)
O(5)	80(20)	3(10)	12(10)	0	10(12)	0

Table IV-5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$x 10^3) for $Pd(PA\text{-}Ph)_2O_2$.

	x	y	z	U(eq)
H(3A)	-562	1404	-445	21
H(3B)	-626	2063	315	21
H(5A)	2733	3547	2079	29
H(5B)	2843	3019	3025	29
H(5C)	1880	3600	2437	29
H(6A)	345	3237	-1115	35
H(6B)	-628	3164	-938	35
H(6C)	-438	2500	-1615	35
H(7A)	-355	162	589	28
H(7B)	-569	702	1359	28
H(7C)	435	157	1769	28
H(8A)	2944	1687	2025	19
H(8B)	2896	2344	1209	19
H(10A)	2040	531	-321	34
H(10B)	2943	540	816	34
H(10C)	2883	1234	37	34
H(12A)	2386	400	2480	22
H(13A)	3741	-170	3899	27
H(14A)	4281	400	5496	28
H(15A)	3397	1508	5698	26
H(16A)	2049	2095	4285	22

Table IV-6. Torsion angles [°] for $Pd(PA\text{-}Ph)_2O_2$.

O(4)#1-Pd(1)-P(1)-C(11)	108.98(13)
O(4)-Pd(1)-P(1)-C(11)	108.46(11)
P(1)#1-Pd(1)-P(1)-C(11)	-71.35(9)
O(4)#1-Pd(1)-P(1)-C(4)	-117.25(13)
O(4)-Pd(1)-P(1)-C(4)	-117.76(11)
P(1)#1-Pd(1)-P(1)-C(4)	62.43(9)
O(4)#1-Pd(1)-P(1)-C(1)	-11.26(13)
O(4)-Pd(1)-P(1)-C(1)	-11.78(10)
P(1)#1-Pd(1)-P(1)-C(1)	168.41(9)
P(1)#1-Pd(1)-O(4)-O(4)#1	-0.8(2)
P(1)-Pd(1)-O(4)-O(4)#1	179.56(13)
C(2)-O(1)-C(1)-C(5)	172.2(2)
C(2)-O(1)-C(1)-C(8)	50.3(3)
C(2)-O(1)-C(1)-P(1)	-68.5(2)
C(11)-P(1)-C(1)-O(1)	171.27(15)
C(4)-P(1)-C(1)-O(1)	61.54(17)
Pd(1)-P(1)-C(1)-O(1)	-60.01(16)
C(11)-P(1)-C(1)-C(5)	-72.6(2)
C(4)-P(1)-C(1)-C(5)	177.64(19)
Pd(1)-P(1)-C(1)-C(5)	56.09(19)
C(11)-P(1)-C(1)-C(8)	53.27(19)
C(4)-P(1)-C(1)-C(8)	-56.46(18)
Pd(1)-P(1)-C(1)-C(8)	-178.01(14)
C(9)-O(2)-C(2)-O(1)	60.5(3)
C(9)-O(2)-C(2)-C(6)	175.5(2)
C(9)-O(2)-C(2)-C(3)	-62.0(2)
C(1)-O(1)-C(2)-O(2)	-54.6(3)
C(1)-O(1)-C(2)-C(6)	-169.6(2)
C(1)-O(1)-C(2)-C(3)	66.1(3)
O(2)-C(2)-C(3)-C(4)	57.8(2)
O(1)-C(2)-C(3)-C(4)	-64.5(3)
C(6)-C(2)-C(3)-C(4)	175.5(2)
C(9)-O(3)-C(4)-C(7)	173.07(19)
C(9)-O(3)-C(4)-C(3)	51.0(3)

C(9)-O(3)-C(4)-P(1)	-65.0(2)
C(2)-C(3)-C(4)-O(3)	-51.1(3)
C(2)-C(3)-C(4)-C(7)	-168.3(2)
C(2)-C(3)-C(4)-P(1)	68.3(2)
C(11)-P(1)-C(4)-O(3)	-51.64(19)
C(1)-P(1)-C(4)-O(3)	54.63(18)
Pd(1)-P(1)-C(4)-O(3)	170.05(13)
C(11)-P(1)-C(4)-C(7)	66.7(2)
C(1)-P(1)-C(4)-C(7)	172.93(18)
Pd(1)-P(1)-C(4)-C(7)	-71.66(19)
C(11)-P(1)-C(4)-C(3)	-169.04(16)
C(1)-P(1)-C(4)-C(3)	-62.77(18)
Pd(1)-P(1)-C(4)-C(3)	52.64(18)
O(1)-C(1)-C(8)-C(9)	-51.5(3)
C(5)-C(1)-C(8)-C(9)	-169.7(2)
P(1)-C(1)-C(8)-C(9)	65.0(2)
C(2)-O(2)-C(9)-O(3)	59.8(3)
C(2)-O(2)-C(9)-C(10)	175.4(2)
C(2)-O(2)-C(9)-C(8)	-62.1(2)
C(4)-O(3)-C(9)-O(2)	-55.1(3)
C(4)-O(3)-C(9)-C(10)	-171.53(19)
C(4)-O(3)-C(9)-C(8)	64.5(3)
C(1)-C(8)-C(9)-O(2)	57.9(3)
C(1)-C(8)-C(9)-O(3)	-63.3(3)
C(1)-C(8)-C(9)-C(10)	176.8(2)
C(4)-P(1)-C(11)-C(16)	-161.42(19)
C(1)-P(1)-C(11)-C(16)	99.7(2)
Pd(1)-P(1)-C(11)-C(16)	-23.6(2)
C(4)-P(1)-C(11)-C(12)	21.4(3)
C(1)-P(1)-C(11)-C(12)	-77.5(2)
Pd(1)-P(1)-C(11)-C(12)	159.21(19)
C(16)-C(11)-C(12)-C(13)	-2.5(4)
P(1)-C(11)-C(12)-C(13)	174.7(2)
C(11)-C(12)-C(13)-C(14)	0.4(4)
C(12)-C(13)-C(14)-C(15)	2.1(4)
C(13)-C(14)-C(15)-C(16)	-2.4(4)

C(14)-C(15)-C(16)-C(11)	0.2(4)
C(12)-C(11)-C(16)-C(15)	2.1(4)
P(1)-C(11)-C(16)-C(15)	-175.2(2)

Symmetry transformations used to generate equivalent atoms:

#1 -x,y,-z+1/2

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