A User-friendly Synthesis of Aryl Arsines and Phosphines

By

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A thesis submitted in partial fulfillment
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in
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To My Supervisor

Professor Kin Shing Chan

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Chi Wai LAI

Department of Chemistry

The Chinese University of Hong Kong

Abbreviations

δ	: chemical Shift	m	: multiplet (NMR)
^{n}Bu	: *n*-butyl	M^{+}	: molecular ion
^{t}Bu	: *tert*-butyl	*m/z*	: mass per charge ratio
Calcd.	: calculated	Me	: methyl
cy	: cyclohexyl	mg	: milligram (s)
d	: day (s)	min	: minute (s)
d	: doublet (NMR)	mL	: milliliter (s)
DABCO	: 1,4-diazabicyclo[2,2,2]octane	mmol	: millimole (s)
dba	: (*E,E*)-dibenzylidieneacetone	MHz	: megahertz
dd	: double doublets	MS	: mass spectrometry
DME	: dimethoxyethane	Nf	: nonafluorobutanesulfonyl
DMF	: dimethylformamide	Np	: naphthyl
DMSO	: dimethylsulfoxide	NMP	: *N*-methylpyrrolidinone
dppe	: diphenylphosphinoethane	NMR	: nuclear magnetic resonance
dppp	: diphenylphosphinopropane	py	: pyridine
EI	: electron impact (MS)	q	: quartet (NMR)
Et	: ethyl	rt	: room temperature
Fn	: Functional groups	s	: singlet (NMR)
GC	: gas chromatography	t	: triplet (NMR)
g	: gram (s)	THF	: tetrahydrofuran
h	: hour (s)	Tf	: trifluoromethanesulfonyl
J	: coupling constant (NMR)	TLC	: thin layer chromatography

Abstract of thesis entitled:

A User-friendly synthesis of aryl arsines and phosphines

Submitted by Chi Wai LAI

for the degree of Master of Philosophy

at The Chinese University of Hong Kong in June 2001

Novel palladium catalyzed phosphination and arsination of aryl triflates were discovered. The newly developed methodology was applied in the synthesis of functionalized triarylphosphines from their corresponding aryl triflates. This convenient synthetic protocol tolerates aldehyde, ketone, ester, nitrile, pyridyl, methyl ether and chloride functional groups. Nitro group was compatible only in arsination without reduction to amine. *ortho*-Substituted aryl triflates were less effective than *meta* and *para*-substituted ones.

These phosphination and arsination were successfully carried out in solvent-free conditions in compatible rate and yields.

摘要

本論文發現了一種新穎的鈀催化下三氟甲磺酸芳基酯的磷化和砷化反應，從而將三氟甲磺酸芳基酯轉化為相應的芳基磷化物和芳基砷化物。這種新方法可以用於多種官能團取代的芳基磷和芳基砷的合成，如：醛、酮、酯基、腈基、吡啶基、甲氧基和氯基，但硝基取代的三氟甲磺酸芳基酯只可以發生砷化反應且不被還原為氨基。另外，鄰位取代的三氟甲磺酸芳基酯反應活性低於對位。

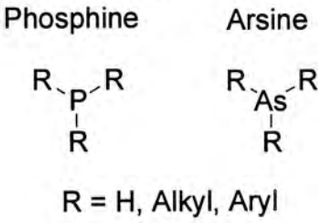
同時，這種磷化和砷化反應在無溶劑條件下，可成功獲得同樣的反應速率和產率。

Chapter 1 General Introduction

1.1 Background of Phosphines and Arsines Ligands in Metal Catalysis

Phosphorous and arsenic are both group 15 elements. Phosphines and arsines are hydrogen or organic derivatives bonded to phosphorus or arsenic center respectively (Fig 1.1.1).[1,2] The bond length between phosphorus and carbon atom is about 0.140 to 0.180 nm. Arsine-carbon bond is longer and varies from 0.148 to 0.200 nm (Table 1.1.1).[1-4]

Figure 1.1.1 Structure of phosphine and arsine



Phosphines and arsines, by virtue of the lone pair electrons, are ligands for metal ions especially in their lower oxidation states. Both electronic effect and steric effect can be tunable in phosphines and arsines ligands by varying the electronic nature and the size of R groups.[1,2]

The steric bulkiness of phosphines and arsines is measured by the cone angles,[1] which is the plane angle at the apex of a cone located at the center of the central metal atom of the ligand and is equal to the effective van der Waals radii of those atoms. A larger cone angle of a phosphine and arsine means that the ligand is more bulky (Table 1.1.1).[1-4]

Table 1.1.1 Structural Data of Phosphines and Arsines[1-4]

Entry	Compound	Cone angles / °	Bond length / nm
1	PH_3	87	0.142
2	PMe_3	118	0.185
3	PPh_3	145	0.183
4	AsH_3	91	0.153
5	$AsMe_3$	123	0.197
6	$AsPh_3$	148	0.196

The development of phosphines coordination chemistry is much more advanced than that of arsines. Likely, the more stable metal-phosphorus bond is one of the possible reasons. The relative synthetic difficulty due to more toxic arsines may be another reason.[3,4]

Coordinating ability of the ligands to metal catalysts also has critical effect in the transition metal catalysis. Generally, oxidative addition and reductive elimination are involved in transition metal catalysis.[1-5] Stronger donor ligands are effective in stabilizing metal complexes especially at the lower oxidation states to prevent the metal from decomposition by precipitation. On the other hand, weaker ligands produce more coordinatively unsaturated metal complexes to enhance reactivity. Consequently, the ideal ligands are a compromise between donor and dissociation ability, and catalysis-specific. Therefore, readily accessible ligands differing in electronic and steric properties are often desired to optimize catalytic efficiency.

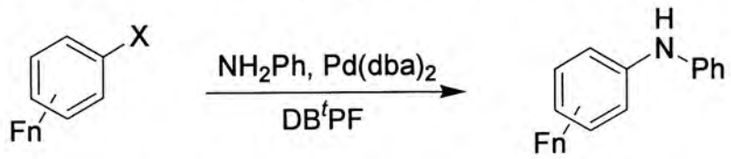
1.2 Electronic Effect of Phosphines and Arsines Ligands in Metal Catalysis

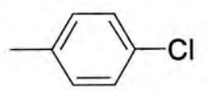
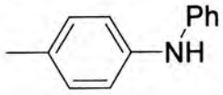
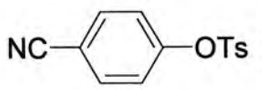
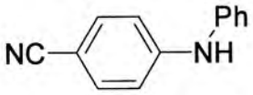
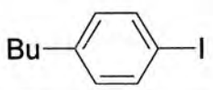
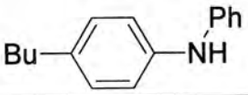
Phosphines and arsines ligands are essential to transition metal catalyzed reactions. In particular, they are widely used as ligands in palladium-catalyzed cross-

coupling processes such as Negishi,[6] Heck coupling,[6] Stille coupling,[7,8] Suzuki cross-coupling[9] and amination reaction.[10]

In 1998, Hartwig reported the first palladium-catalyzed amination of unreactive tosylate by using electron-rich and sterically bulky phosphine ligands 1,1'-bis(di-*tert*-butylphosphino)ferrocene (DB^{t}PF) and its derivatives.[10] This amination reaction is compatible to aryl halides and tosylates. The authors suggested that these ligands could provide the required electron rich and sterically bulky metal center to facilitate oxidative addition and reductive elimination respectively. Hence, they can activate the unreactive species and accelerate the reaction rate (Table 1.2.1).[10]

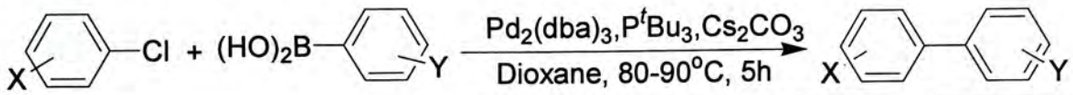
Table 1.2.1 Amination of Aryl Halides and Tosylates



Entry	ArX	Product	Conditions	Yield /%
1			110°C, 24h	93
2			110°C, 16h	79
3			r.t., 24h	95

At the same time, Fu and co-workers reported the first palladium catalyzed Suzuki cross-couplings of unreactive aryl chlorides with arylboronic acids by using electron rich and sterically-hindered tri-*tert*-butylphosphine ligand combined with a palladium catalyst. Even unreactive aryl chlorides can react with this powerful catalytic system (Table 1.2.2).[11]

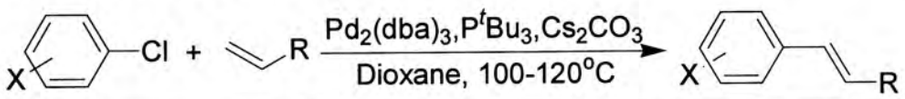
Table 1.2.2 Suzuki Cross-coupling of Aryl Chlorides



Entry	X	Y	Yield /%
1	4-Me	H	87
2	4-MeCO	H	91
3	4-MeO	H	89
4	4-NH_2	H	92
5	4-Me	4-CF_3	86

Moreover, the $P^tBu_3/Pd(OAc)_2$ catalyst system is able to activate aryl chlorides in Heck reaction (Table 1.2.3).[13]

Table 1.2.3 Heck Coupling of Aryl Chlorides



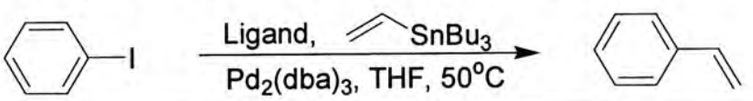
Entry	X	R	Yield /%
1	H	CO_2Me	76
2	4-MeCO	Ph	74
3	4-MeO	CO_2Me	82
4	4-MeO	Ph	74
5	2-Me	Ph	70

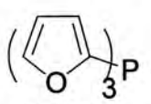
The author suggested that faster reaction rate in these transition metal catalyzed cross coupling reactions is due to faster oxidative addition and reductive elimination associated with a coordinately-unsaturated electron rich metal with a bulky phosphine ligand. Since the electron rich tri-*tert*-butylphosphine ($^tBu_3P$) donates electron to the metal catalyst and forms an electron-rich and coordinatively unsaturated monophosphine-Pd (1:1) complex, oxidative addition is possible even for unreactive substrates. The sterically hindered $^tBu_3P$ further promotes the rate of reductive elimination from the palladium center.[11-13]

The analogous arsines are much less explored and only a few reports have been published in the application for catalysis. Only triphenylarsine is most often used. Possibly, it is the only accessible arsine. Triphenylarsine, compared with triphenylphosphine, gives faster rates and higher yields in some transition metal catalyzed reactions such as Stille,[14] Heck,[15] Negishi,[16] Suzuki coupling,[17] epoxidation,[18] hydroformylation,[19] carbonylation[20] and cyclization of an allylic enyne.[21]

Farina and co-workers reported that a large rate acceleration in the Stille reaction occurred when triphenylarsine instead of triphenylphosphine was used (Table 1.2.4).[22] Table 1.2.4 shows the results that electron-withdrawing ligands are more effective. The author suggested that transmetalation is the rate-determining step in the catalytic cycle. The electron-poor ligands more readily dissociated from Pd(II) and allow faster rate of reaction.

Table 1.2.4 Ligands effect in Stille coupling



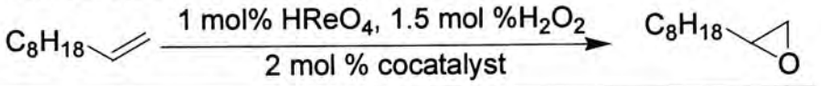
Entry	Ligand	Rel rate	Yield / %[a]
1	PPh_3	1	15
2	$MePPh_2$	0.07	<2
3	$Ph_2PC_6F_5$	24	>95
4		105	>95
5	$AsPh_3$	1100	>95

[a] HPLC yield after 72 hours

Sheldon et al. found that the combination of tertiary arsines with perrhenic acid gave a catalyst which effectively catalyzed the epoxidation of a variety of olefins

(Table 1.2.5).[18] Methyldiphenylarsine is most effective in the epoxidation while phosphines gave only a little enhancement in effeciency.

Table 1.2.5 Result of epoxidation of dec-1-ene

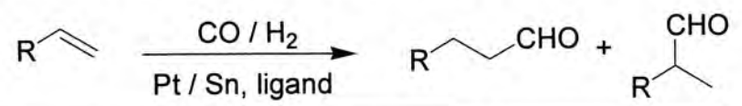


Entry	Cocatalyst	Initial rate / h^{-1}	Yield / %[a]
1	None	0	0
2	PPh_3	0.1	4
3	$AsPh_3$	1.7	62
4	$MeAsPh_2$	1.8	83
5	Bu_2AsPh	1.0	65
6	$AsBu_3$	0.6	46

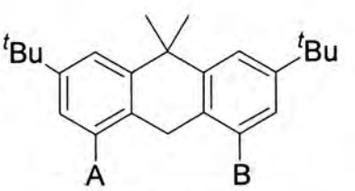
[a]Maximum yield in 168 hour.

In 2000, van Leeuwen and co-worker reported that a mixed arsine-phosphine ligand, rather than phosphine-phosphine or arsine-arsine ligand, is the most efficient catalyst for selective hydroformylation of terminal alkenes.[19] This mixed-donor phosphine-arsine ligand constitutes ten times more active than phosphine ligands.

Table 1.2.6 Hydroformylation of Oct-1-ene at 60°C



Entry	A	B	% *n*-Nonanal	TOF
1	PPh_2	PPh_2	95	18
2	$AsPh_2$	$AsPh_2$	92	210
3	$AsPh_2$	PPh_2	96	350



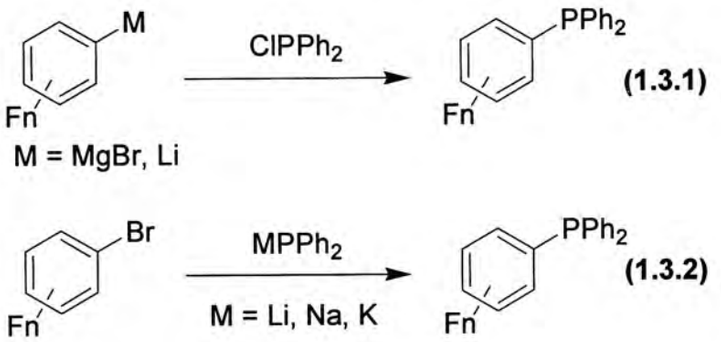
Ligand

As seen from the above examples, catalysis depends on easily accessible ligands to allow optimization of catalytic efficiency.

1.3 Synthesis of Aryl Phosphines

Triarylphosphines are one of the most important classes of controller ligands in transition metal catalyzed reactions.[23] In order to modify the catalysis, there is a necessity to incorporate functional group in aromatic phosphines. However, synthetic methods available are limited in scope.

Traditional methods for preparation of aryl phosphines can be divided into two major categories. The first category involves the reactions of aryl Grignard or organolithium reagents with chlorodiarylphosphines (eq 1.3.1) and the reactions of phosphenide anions with organic electrophiles (eq 1.3.2).[24]

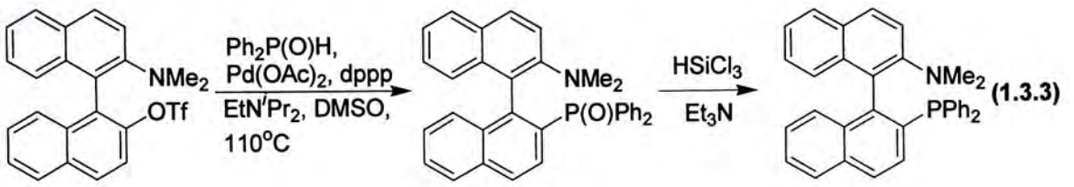


(1.3.1)

(1.3.2)

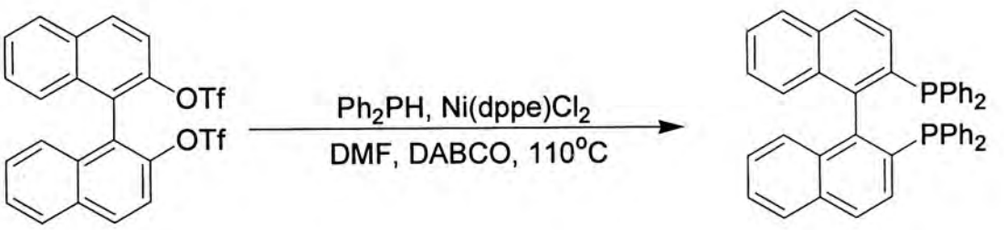
Though these methods are straightforward, they are not tolerant towards base sensitive groups such as formyl and acetyl. Previous synthesis of these kinds of phosphines require extra protection and deprotection steps.[1] Furthermore, these methods are only applicable for aryl bromides and aryl iodides, but not aryl triflates.

The second category is transition metal catalyzed phosphination. Recently, several phosphination methods have been discovered such as palladium catalyzed phosphination using diphenylphosphine oxide as the phosphinating agent reported by Saá, Ding and Mikami et al.[25] Though the phosphination agent is air stable, an extra reduction step is required to obtain the phosphine product (eq 1.3.3).



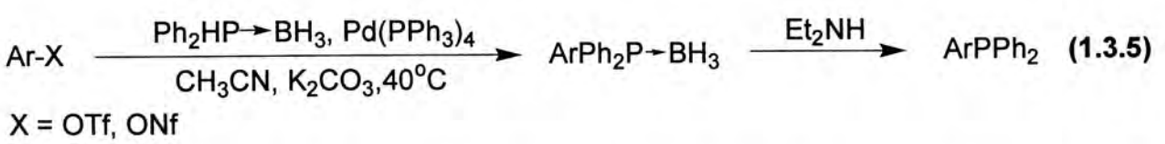
(1.3.3)

Nickel catalyzed phosphination of aryl triflates using diphenylphosphine as the phosphinating agent was reported by Cai et al (eq 1.3.4).[26] The disadvantage of this method is the use of highly air and moisture sensitive diphenylphosphine[1] as the phosphinating agent.



(1.3.4)

In order to avoid the use of air and moisture sensitive diphenylphosphine, Lipshutz and co-workers developed palladium catalyzed phosphination of aryl nonaflates and triflates by using air-stable diphenylphosphine-borane instead of diphenylphosphine as the phosphinating agent.[27] However, an extra deprotection by base is required for removing the borane adduct. Furthermore, pyridine containing substrates are not compatible in this phosphination (eq 1.3.5).

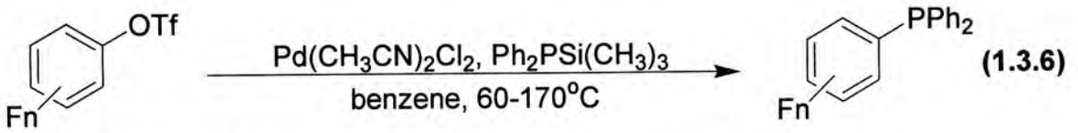


(1.3.5)

X = OTf, ONf

Stille and co-workers have developed palladium catalyzed phosphination of aryl halides using (trimethylsilyl)diphenylphosphine (Ph_2PSiMe_3) as the phosphinating reagent.[28] This phosphination tolerates a variety of functional groups such as ester, ketone, halides, methyl ether and trifluoromethyl groups. The

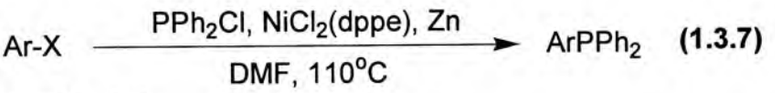
phosphinating agent is fairly air stable. However, the phosphinating agent is moisture sensitive and commercially unavailable. The method is also limited to aryl iodides (eq 1.3.6).



(1.3.6)

Fn = $COCH_3$, $COOCH_3$, Cl, CF_3, OCH_3

Other phosphination method using chlorodiphenylphosphine was reported by Ager et al. Zinc was used as the reductant in the reduction of Ni(II) catalyst into Ni(0).[29] The advantage of this method is that many functional groups such as ketone, aldehyde, methyl ether and amine are compatible and the phosphinating reagent is much cheaper than diphenylphosphine. However, chlorodiphenylphosphine is highly air and moisture sensitive reagent (eq 1.3.7).[1]



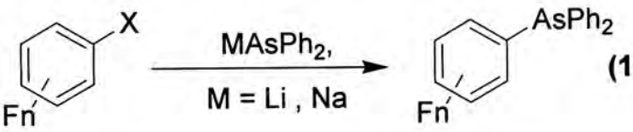
(1.3.7)

X = Br, OTf

1.4 Synthesis of Aryl Arsines

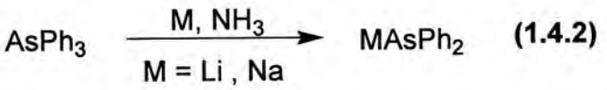
Aryl arsines are prepared in a manner similar to their phosphine analogues.[1,4] Traditional preparation of tertiary arsines can be classified into three methods. The first method involves the reactions of aryl bromides or iodides with sodium or lithium diphenylarsenide (eq 1.4.1) which is prepared *in situ* from the reaction of triphenylarsine with Li or Na in liquid ammonia (eq 1.4.2).[30] The straightforward preparation of arsinating reagent is the advantage of this method. However, this method is limited to base insensitive compounds.

A recently example by Novak and co-workers is illustrated by the synthesis of the water-soluble aryl arsine by the reaction of potassium diphenylarsenide and the sulfonated aryl fluoride (eq 1.4.3).[31]

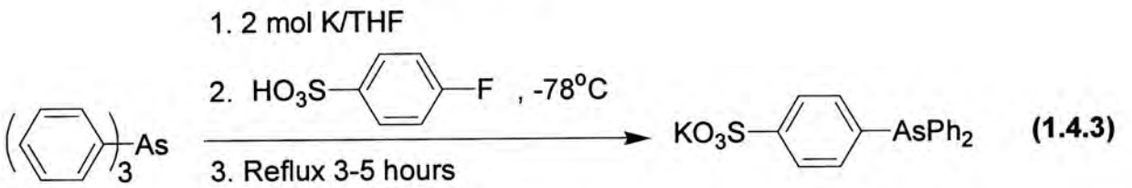


(1.4.1)

X = Br, I

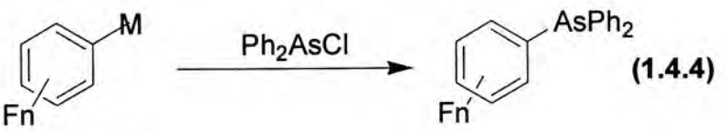


(1.4.2)



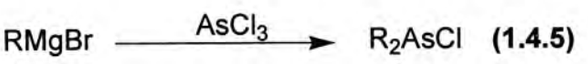
(1.4.3)

The second method is the reaction of aryl Grignard reagents with chlorodiphenylarsine (Ph_2AsCl) (eq 1.4.4).[2,4] However, it is limited to base insensitive compounds. Furthermore, Ph_2AsCl is not commercially available and is prepared by the reaction between highly toxic and volatile arsenic trichloride with phenyl magnesium bromide (eq 1.4.5).[2,4]



(1.4.4)

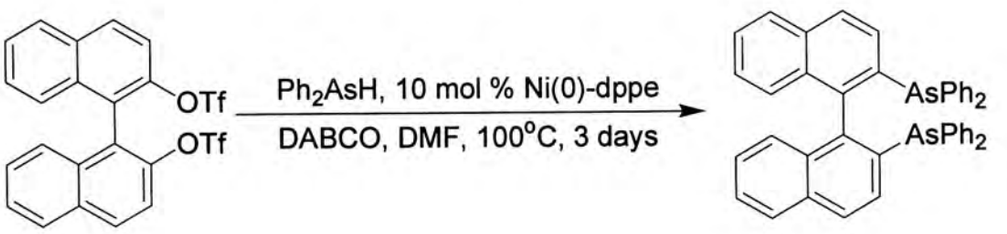
M = Li, Mg



(1.4.5)

The third method is the transition metal catalyzed arsination. Shibasaki and co-workers have reported the nickel catalyzed arsination of aryl triflates.(eq 1.4.6)[32]

The disadvantage of the method is the use of highly toxic, air- and moisture-sensitive diphenylarsine (Ph_2AsH) which is not commercially available.

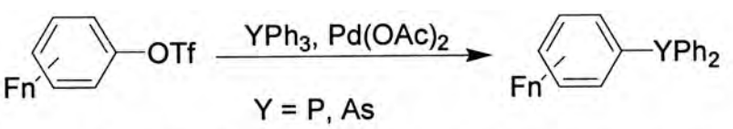


(1.4.6)

1.5 The Objective of This Work

As shown above, phosphines and arsines are important ligands in transition metal catalyzed reactions. In order to enhance the efficiency of transition metal catalysis, modification of electronic effect of ligands are necessary. However, the reported synthetic methods of phosphines and arsines are limited in scopes.

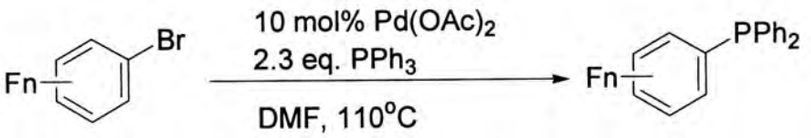
This thesis concerns a general, user-friendly synthesis of aryl phosphines and arsines using air- and moisture- stable triarylphosphines and triphenylarsine as the phosphinating and arsinating reagents respectively (Scheme 1.5.1).[33-35]



Scheme 1.5.1 Pallladium catalyzed phosphination and arsination

Chapter 2 Palladium Catalyzed Phosphination of Aryl Triflates

Recently, a novel phosphination methodology of aryl bromides using economical triarylphosphines as the diaryl phosphinating reagents and $Pd(OAc)_2$ catalyst has been developed in our laboratory (eq 2.1).[33] This method was found to be compatible with many functional groups such as ketone, aldehyde, ester, nitrile, methoxy and pyridyl groups. Protection/deprotection steps are not required and triarylphosphines are inexpensive or readily available too. Moreover, triarylphosphines are air and moisture stable. Thus, syntheses of substituted aryl phosphines are operationally simple, user-friendly and economically attractive. Since aryl bromides and triflates are similar in chemical reactivity, we would like to extend the phosphination from aryl bromides to triflates.



(2.1)

Fn = aldehyde, chloride, cyano, ester, methyl ether and ketone

2.1 Synthesis of Aryl Triflates

The leaving-groups ability increases with the decreasing basicity of an anion (X^-) or the increasing acidity of its conjugate acid (HX). Thus, we can estimate the leaving-group ability by comparing the pK_a values of the acids (Table 2.1.1).[36]

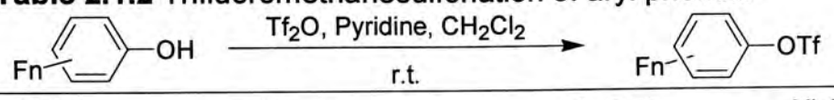
Table 2.1.1 The acidity of different acids

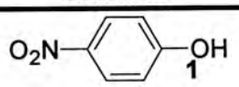
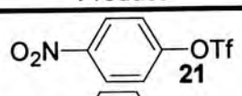
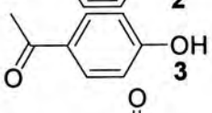
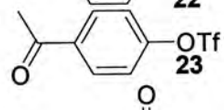
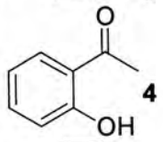
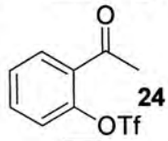
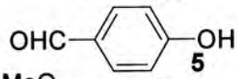
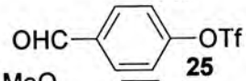
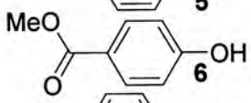
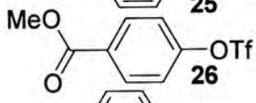
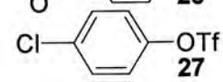
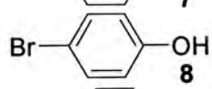
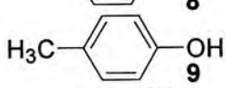
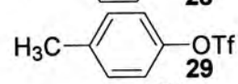
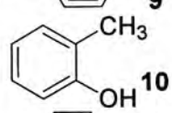
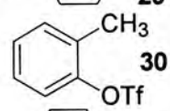
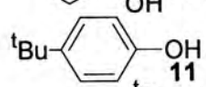
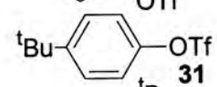
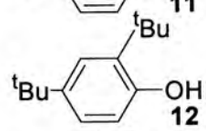
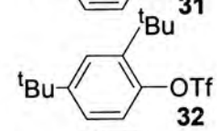
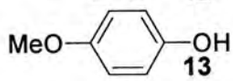
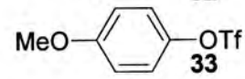
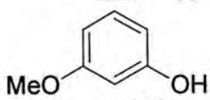
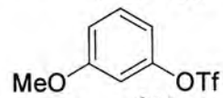
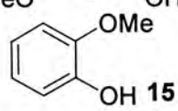
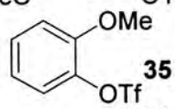
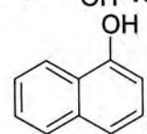
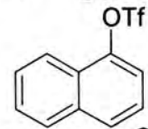
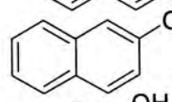
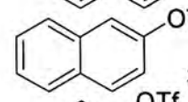
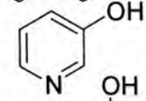
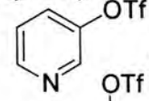
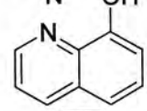
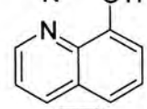
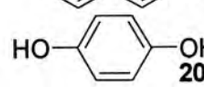
Name	Acid (HX)	pK_a [36]
Nonaflic acid	HONf	-6.9
Triflic acid	HOTf	-6.4
Hydrogen iodide	HI	-5.2
Hydrogen bromide	HBr	-4.7
Hydrogen chloride	HCl	-2.2

As the acidities of trifluoromethanesulfonic acid (triflic acid) and nonafluoro-*n*-butanesulfonic acid (nonaflic acid) are very strong, their leaving group abilities are higher than those of bromide and chloride ions.

As phenols are easily accessible, they were converted into the corresponding aryl triflates in high yields with trifluoromethanesulfonic anhydride (triflic anhydride, Tf_2O) in the presence of excess pyridine in dry dichloromethane for 1 to 2 hours at room temperature.[37] Table 2.1.2 lists the syntheses of aryl triflates.

Table 2.1.2 Trifluoromethanesulfonation of aryl phenols



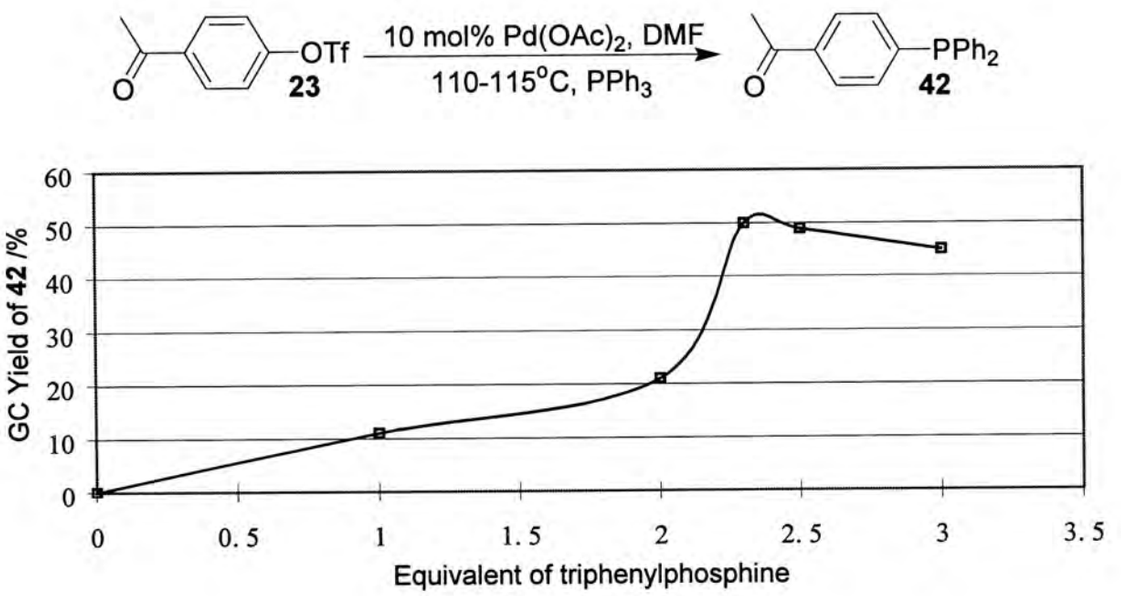
Entry	Substrate	Product	Yield / % [a]
1	 **1**	 **21**	90
2	 **2**	 **22**	96
3	 **3**	 **23**	87
4	 **4**	 **24**	85
5	 **5**	 **25**	85
6	 **6**	 **26**	91
7	 **7**	 **27**	93
8	 **8**	 **28**	91
9	 **9**	 **29**	92
10	 **10**	 **30**	82
11	 **11**	 **31**	90
12	 **12**	 **32**	88
13	 **13**	 **33**	88
14	 **14**	 **34**	88
15	 **15**	 **35**	82
16	 **16**	 **36**	79
17	 **17**	 **37**	92
18	 **18**	 **38**	90
19	 **19**	 **39**	92
20	 **20**	**40**	95

[a] Isolated yield

2.2 Palladium Catalyzed Phosphination of Aryl Triflates

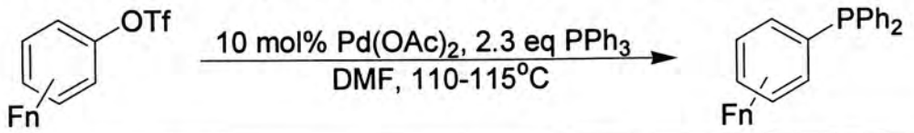
As the amount of triphenylphosphine was found to be crucial in the phosphination of aryl bromides,[33-35] the optimal amount of triphenylphosphine in the phosphination of aryl triflates using 4-acetylphenyltriflate was found to be about 2.3 equivalents (Figure 2.1).

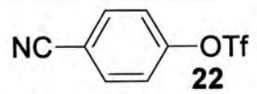
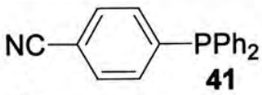
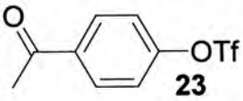
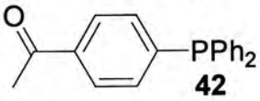
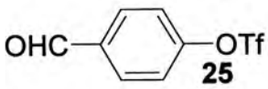
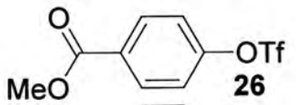
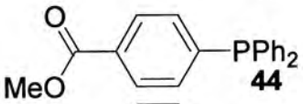
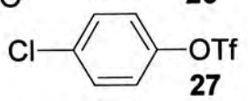
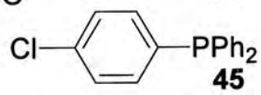
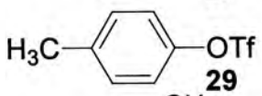
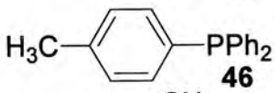
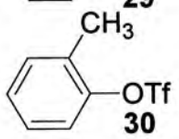
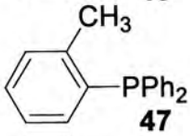
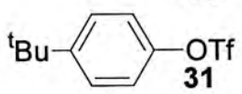
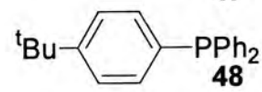
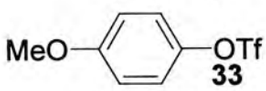
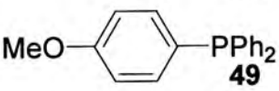
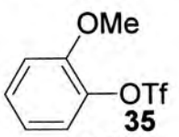
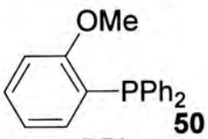
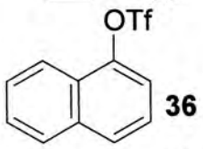
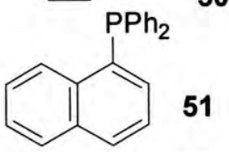
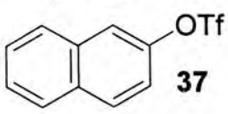
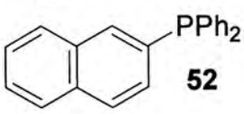
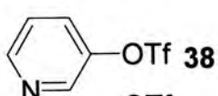
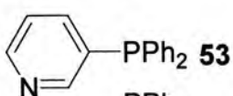
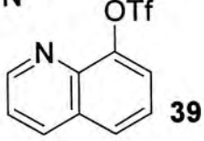
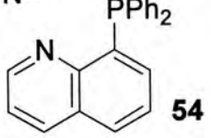
Figure 2.1 Effect of a triphenylphosphine on the phosphination of 4-acetylphenyltriflate



Aryl triflates were found to undergo phosphination successfully using 10 mole % $Pd(OAc)_2$ and 2.3 equivalents of PPh_3 in DMF at 110-115 °C in 2 to 8 hours (Table 2.2.1). Electron-poor aryl triflates gave higher yields than electron-rich aryl triflates.[35] One possible reason is the oxidation stability of electron deficient phosphines to phosphine oxide is higher than that of electron-rich phosphines.[1,3] Most *para* and *meta*-substituted aryl triflates yielded their corresponding phosphines in about 30-38% yield. The rates of the phosphination of aryl triflates were faster than those of aryl bromides in a manner consistent with leaving group ability.[33,35]

Table 2.2.1 Results of palladium catalyzed phosphination of aryl triflates



Entry	Substrates	Products	Time/h	Yield[a] /%
1	 **22**	 **41**	3	38
2	 **23**	 **42**	2	37
3	 **25**	 **43**	3	31
4	 **26**	 **44**	5	30
5	 **27**	 **45**	5	45[b]
6	 **29**	 **46**	4	45[b]
7	 **30**	 **47**	5	67[b]
8	 **31**	 **48**	6	50[b]
9	 **33**	 **49**	6	20 (25)[b]
10	 **35**	 **50**	8	28
11	 **36**	 **51**	16	27[b]
12	 **37**	 **52**	4	51[b]
13	 **38**	 **53**	24	20 (33)[b]
14	 **39**	 **54**	72	45

[a] Isolated yield was reported.

[b] GC yield was reported using anthracene as the internal standard.

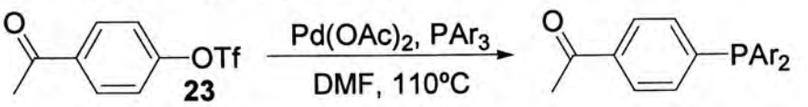
The rates of reaction were slower for *ortho*-substituted aryl triflates. 2-(Diphenylphosphino)anisole **(50)** and 1-(diphenylphosphino)naphthalene **(51)** required longer reaction time. Extremely sterically hindered aryl triflates did not undergo phosphination (Table 2.2.3, entries 2 and 5). This might be due to steric hindrance in the formation of the phosphonium salt or oxidative addition of phosphonium salt.[38] (See mechanistic discussion in Chapter 2.3)

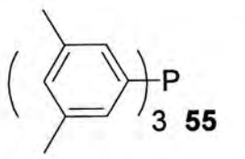
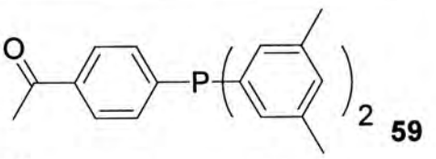
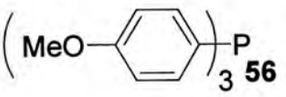
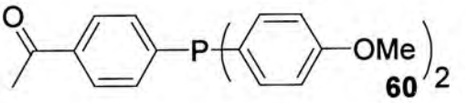
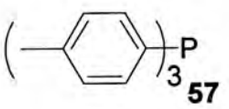
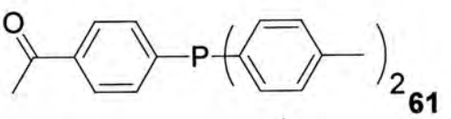
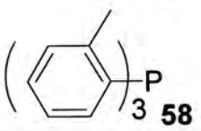
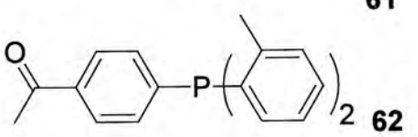
4-(Diphenylphosphino)chlorobenzene **(45)**, 4-(diphenylphosphino)toluene **(46)**, 2-(diphenylphosphino)toluene **(47)**, 4-(diphenylphosphino)*tert*-butylbenzene **(48)**, 1-(diphenylphosphino)naphthalene **(51)** and 2-(diphenylphosphino)naphthalene **(52)** could not be isolated since the R_f values of these phosphines were identical to that of triphenylphosphine. Therefore, the yields of the reaction were determined by using calibrated integration of an authentic sample of phosphines with anthracene as the internal standard in GC-MS analysis.

Pyridyl triflates were also compatible but slower in rates. Presumably, the coordination between the palladium catalyst and heterocyclic nitrogen atom reduces the concentration of catalytically active palladium species and therefore the rate of the reaction.

Triarylphosphines were found to be effective diaryl phosphinating reagents. 4-(Bisxylylphosphino)acetophenone **(59)**, 4-[di(4-methoxyphenyl)phosphinoaceto-phenone **(60)** and 4-[di(4-tolyl)phosphino]acetophenone **(61)** were successfully synthesized though longer reaction time was required. However, 4-[di(2-tolyl)-phosphino]acetophenone **(62)** could not be synthesized presumably due to steric constrain (Table 2.2.2).

Table 2.2.2 Result of palladium catalyzed phosphination of aryl triflate using triarylphosphines

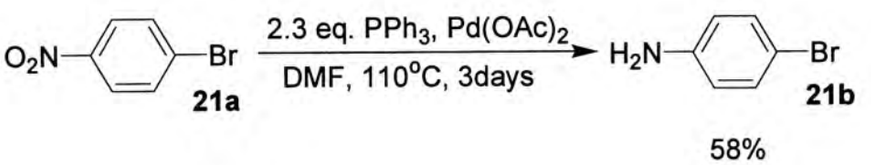


Entry	PAr_3	Products	Time/h	% Yield[a]
1			8	28
2			6	24
3			8	30
4			72	No rxn[b]

[a] Isolated yield was reported

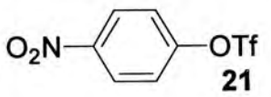
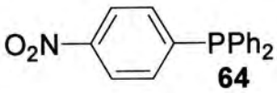
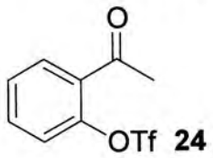
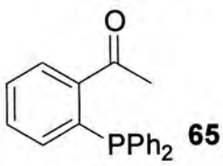
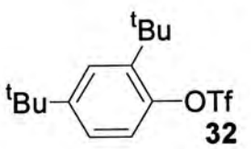
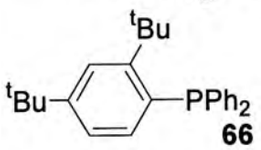
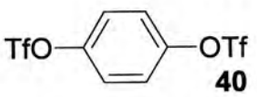
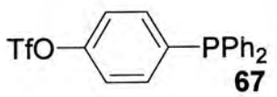
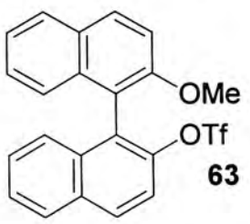
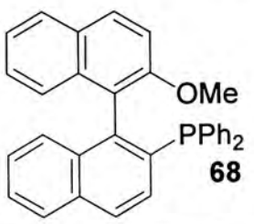
[b] Starting material was not consumed

Functional group limitation still existed in this phosphination. The nitro-substituted phenyl triflate is not compatible in phosphination (Table 2.2.3). The nitro group was reduced to an amino group by triphenylphosphine.[39] Indeed, 4-bromonitrobenzene was reduced to 4-bromoaniline within 3 days in 58% yield (eq 2.2.1).



(2.2.1)

Table 2.2.3 Unsuccessful palladium catalyzed phosphination of aryl triflates

Entry	Substrates	Expected Products	Time/h	Yield / %
1	 **21**	 **64**	48	Nil[a]
2	 **24**	 **65**	96	Nil[a]
3	 **32**	 **66**	96	Nil[a]
4	 **40**	 **67**	96	Nil[a]
5[b]	 **63**	 **68**	120	Nil[c]

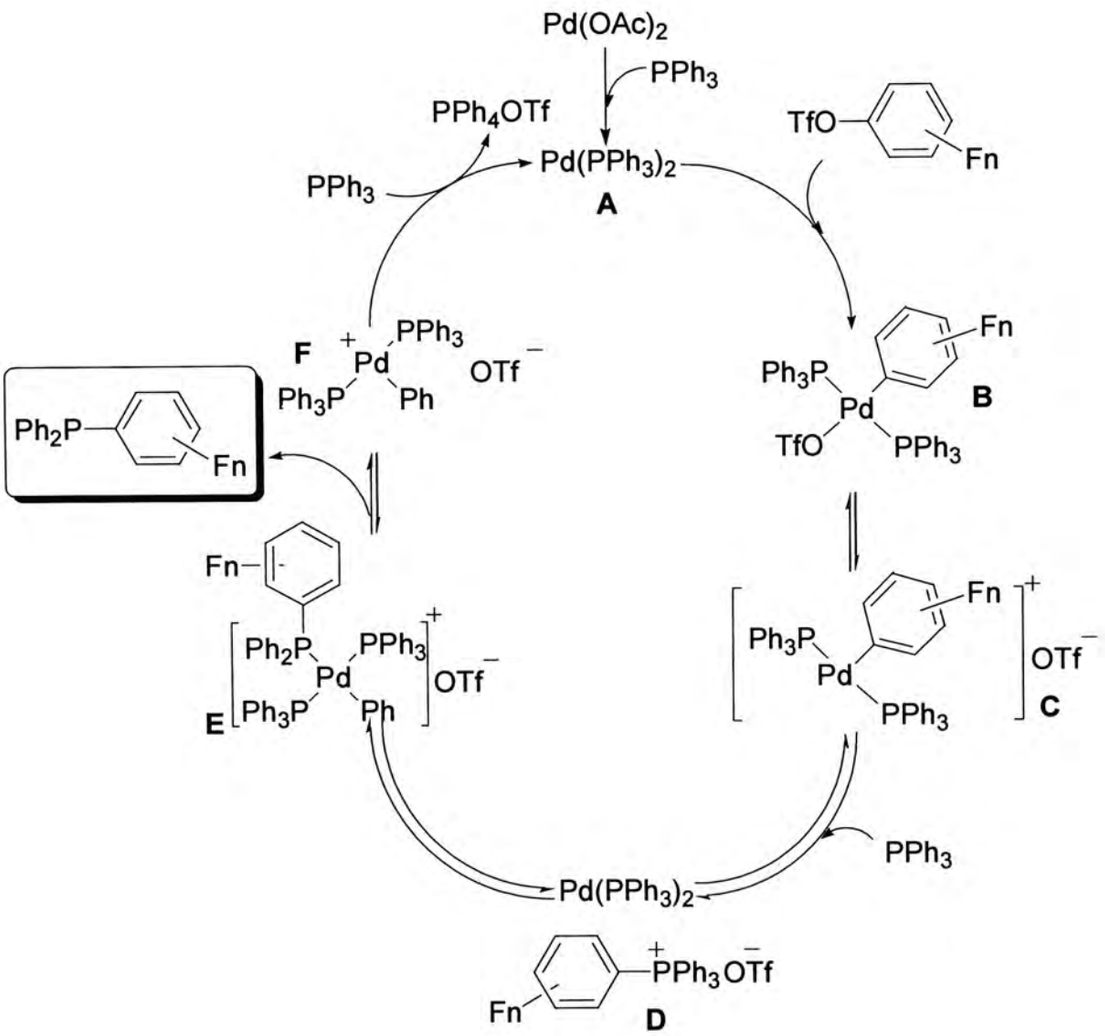
[a] Starting material was consumed within 24 hours.
[b] Temperature was increased to 130°C.
[c] Starting material was not consumed.

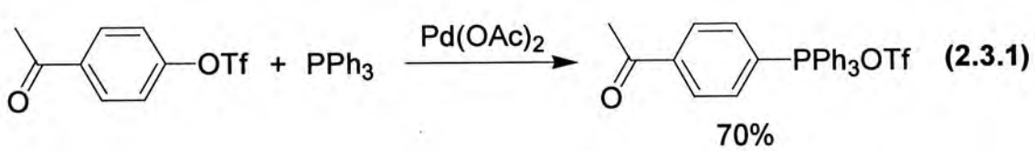
2.3 Mechanistic Studies of Phosphination

A plausible mechanism for the phosphination starts with *in situ* reduction of $Pd(OAc)_2$ to PdL_2 (L = triarylphosphines) complex **A** by triarylphosphines (Scheme 2.3.1).[40] Then, oxidative addition of an aryl triflates to this Pd(0) species to yield complex **B**.[38,41-42] Since triflate is a non-coordinated anion, rapid dissociation occurs and complex **C** is formed. The complex **C** subsequently undergoes reductive elimination with triarylphosphines to give the phosphonium salt complex **D**.[38] In the case of phosphination reaction of 4-acetylphenyltriflate, the 4-acetylphenyltriphenyl phosphonium salts was isolated in 70% crude yield and a peak appeared at δ 24.3

ppm in ^{31}P NMR supporting the existence of phosphonium salt intermediate (eq 2.3.1).[43] The phosphonium salt complex **D** then undergoes oxidative addition with the palladium(0) species to generate complex **E**. Ligand dissociation occurs to form the desired substituted phosphines product and complex **F**. Finally, complex **F** undergoes ligand substitution by triphenylphosphine to regenerate the Pd(0) species and yields tetraphenylphosphonium salt.

Scheme 2.3.1 Proposed mechanism of the phosphination of aryl triflates





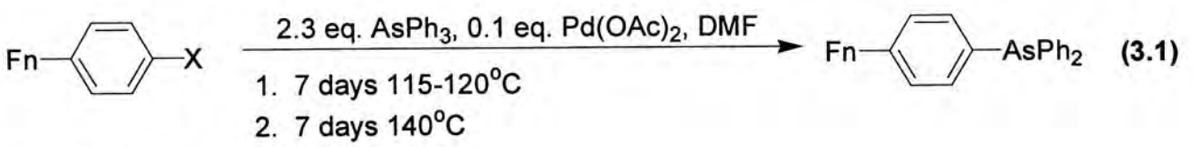
(2.3.1)

In summary, the palladium catalyzed phosphination of aryl triflates using triarylphosphines as the phosphinating reagents were successfully developed. This methodology tolerated various functional groups such as aldehyde, chloride, cyano, ester, ketone, methyl ether and pyridyl groups.

Chapter 3 Palladium Catalyzed Arsination of Aryl Triflates

Arsines are extremely useful ancillary soft ligands in homogenous catalysis but they are less explored.[2] Arsines coordinate to metal and prevent the metal complex in its low oxidation states from precipitation.[22] A number of studies has demonstrated that the use of triphenylarsine instead of triphenylphosphine ligand gave a dramatic reaction rate enhancement and even regioselectivity improvement in many transition metal catalyzed reactions, such as Stille,[14] Heck,[15] Negishi,[16] Suzuki coupling,[17] epoxidation,[18] hydroformylation,[19] carbonylation[20]and cyclization of an allylic enyne.[21] Though arsines are useful ligands and play important roles in catalysis, the preparation of tertiary aryl arsines are limited in scope. In order to extend the scope of the palladium catalyzed phosphination, an analogous arsination was also investigated.

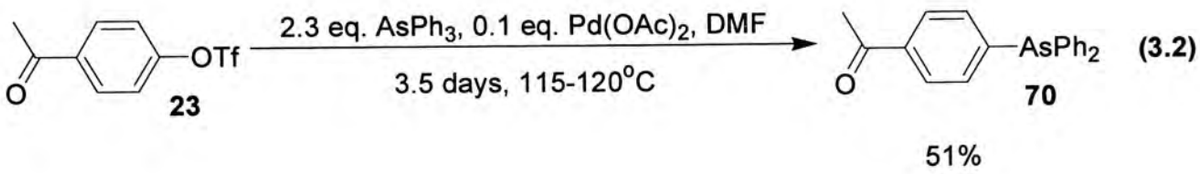
4-Bromoacetophenone and iodotoluene were used as prototype substrates for aryl bromide and iodide in arsination (eq 3.1). Though the desired product was observed by GC-MS analysis in both cases, the rate of arsination reaction was very slow. Even after one-week at elevated temperature of 140°C, starting materials remained. Additions of $NaBF_4$, $NaClO_4$ and Bu_4NPF_6 salts were not beneficial.



(3.1)

a. Fn = CH_3CO, X = Br
b. Fn = CH_3 , X = I
Starting material was not consumed after 2 weeks reaction.

To our delight, 4-acetylphenyltriflate was found to undergo successful palladium catalyzed arsination to give 4-diphenylarsinoacetophenone 51% yield at 120 °C in 3.5 days (eq 3.2). This initial result encouraged us to optimize the reaction conditions of solvents, catalysts, amounts of triphenylarsine and temperature.

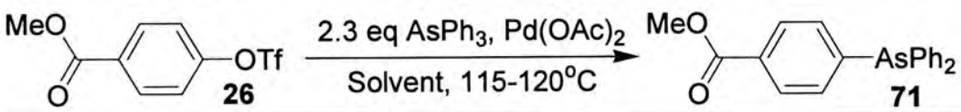


23 **70** 51% **(3.2)**

3.1 Solvent and Catalyst Screening in Palladium Catalyzed Arsination

Four aprotic solvents were tested for the palladium catalyzed arsination reaction. Polar aprotic solvents such as DMF were found to give higher yield (Table 3.1.1).[44] THF, a less polar solvent, was not effective at all and the starting material did not consume.

Table 3.1.1 Solvent screening of palladium catalyzed arsination



26 **71**

Entry	Solvent	Dielectric constant[44]	Time / days	Yield / %[a]
1	DMF	36.7	3.5	51
2	NMP	32.0	5.0	34
3	DMSO	46.6	5.0	40
4	THF	7.6	10.0	0[b]

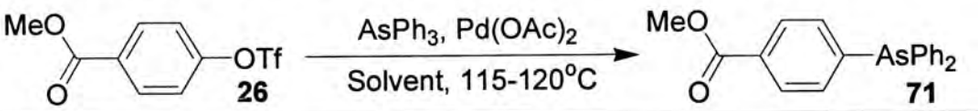
[a] Isolated yield was reported.
[b] Starting material was not consumed.

Both $Pd(OAc)_2$ and $Pd_2(dba)_3$ were found to be active catalysts in the arsination. $Pd(OAc)_2$ was preferred to $Pd_2(dba)_3$ because the dba ligand dissociated in the reaction had similar R_f values with most arsine products making purification by column chromatography very difficult. Other complexes such as $PdCl_2$, $PdCl_2(CH_3CN)_2$, $PtCl_2$ and $Ni(OAc)_2$ were not effective.

3.2 Stoichiometry of Triphenylarsine

As the amount of PPh_3 added in the palladium catalyzed phosphination was very crucial, the amount of $AsPh_3$ added was therefore investigated (Table 3.2.1, Figure 3.1). At least two equivalents of $AsPh_3$ were required to achieve high yield. The optimized amount of $AsPh_3$ was found to be about 2.3 equivalents. The saturation curve in the arsination was in direct contrast with that obtained in the phosphination where more PPh_3 added caused a rapid reduction of product yield (Figure 3.1). Presumably, the PPh_3 was bound to palladium more tightly and inhibited the catalysis while arsine, being a weaker coordinating ligand, did not show such inhibition effect.[2,4,14]

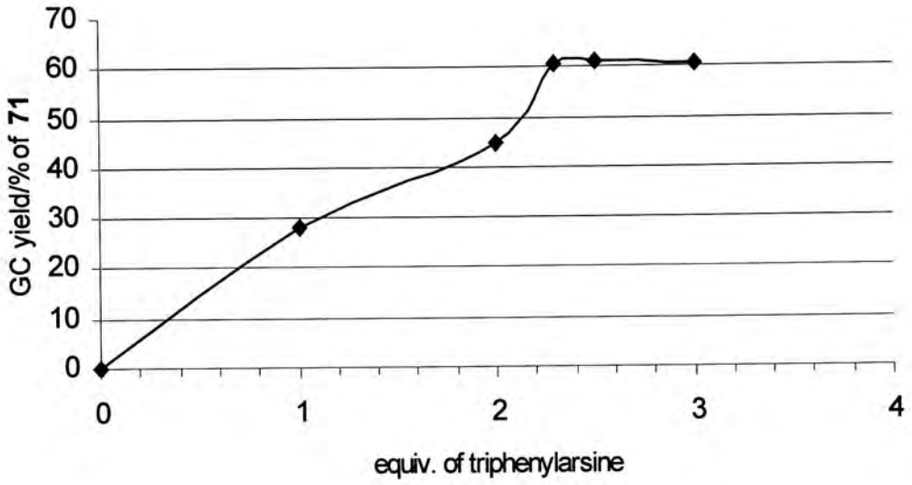
Table 3.2.1 Effect of $AsPh_3$ added in Palladium Catalyzed Arsination



Entry	Equivalence of $AsPh_3$	Yield / %[a]
1	0.0	0
2	1.0	28
3	2.0	45
4	2.3	60
5	2.5	61
6	3.0	60

[a] GC Yield using anthracene as the internal standard

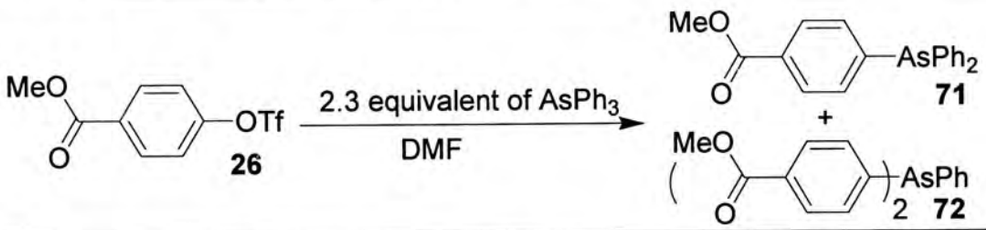
Figure 3.1 Stoichiometry of triphenylarsine



3.3 Temperature Effect of Arsination

The optimized reaction temperature was found to be at 115-120 °C (Table 3.3.1). At lower temperature, starting material did not consume completely or longer reaction time was required. At 140 °C, undesirable disubstituted arsinated side-product was also observed together with mono-substituted product (Table 3.3.1).

Table 3.3.1 Temperature effects in arsination



Entry	Temp / °C	Time / day	Yield of **71** /%[a]	Yield of **72** /%[a]
1	below 110	14	0	0
2	110-115	10	46	0
3	115-120	4.5	48	trace[b]
4	115-120	6	45	4[b]
5	140	3	31	13

[a] Isolated yield was reported.

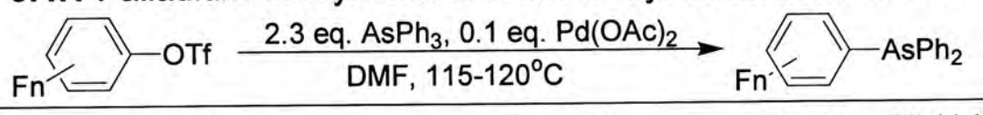
[b] Disubstituted arsine was only observed on GC-MS.

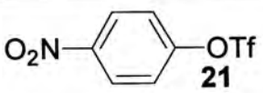
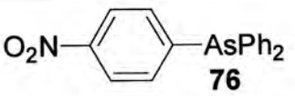
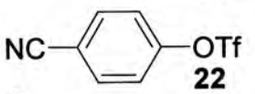
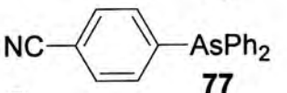
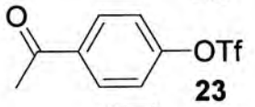
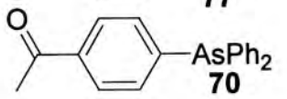
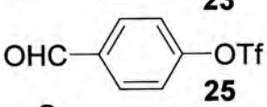
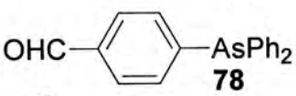
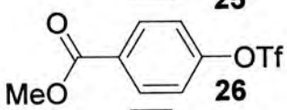
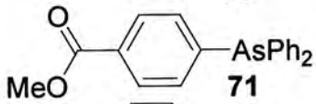
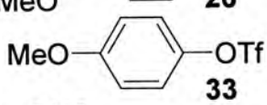
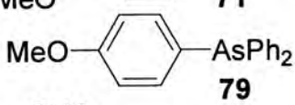
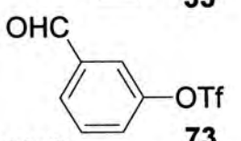
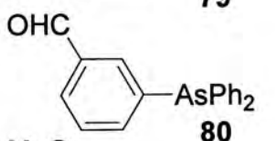
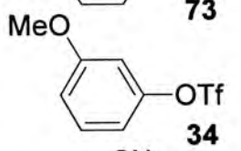
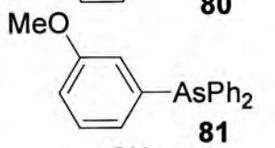
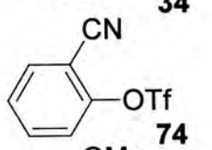
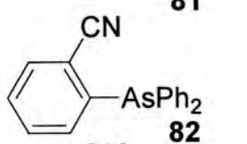
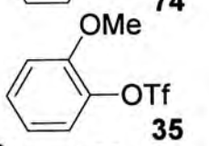
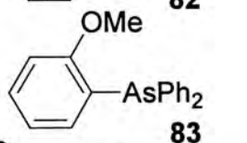
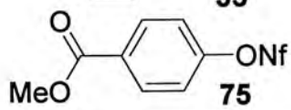
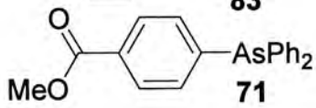
[c] GC yield was reported.

3.4 Results of Palladium Catalyzed Arsination

The optimized palladium catalyzed arsination conditions were applied to functionalized aryl triflates. Aryl triflates were arsinated using 10 mol % palladium(II) acetate as the catalyst with 2.3 equivalents of $AsPh_3$ in DMF at 115-120 °C in about 5 days to give aryl arsines in moderate yields (Table 3.4.1).

Table 3.4.1 Palladium catalyzed arsination of aryl triflates and nonaflates

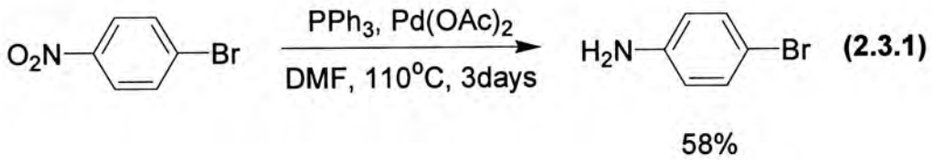


Entry	Substrates	Products	Time/d	Yield / %[a]
1	 **21**	 **76**	4.5	41
2	 **22**	 **77**	4.0	53
3	 **23**	 **70**	3.5	51
4	 **25**	 **78**	4.0	48
5	 **26**	 **71**	4.5	48
6	 **33**	 **79**	4.5	43
7	 **73**	 **80**	4.5	46
8	 **34**	 **81**	4.5	46
9	 **74**	 **82**	5.0	31
10	 **35**	 **83**	3.5	43
11	 **75**	 **71**	4.5	49

[a] Isolated yield was reported.

This arsination is compatible with functional groups such as aldehyde, cyano, ester, ketone, nitro, and methyl ether. Moreover, it is amenable with *ortho*, *meta* and *para* substituted aryl triflates. Comparing the rates of arsination of *para*-substituted aryl triflates, the arsination is independent on the electronic effect. In the case of *ortho*-substituted aryl triflate, 2-methoxyphenyltriflate reacted faster than 2-cyanophenyltriflate. Presumably, the stronger coordination of cyano group to palladium catalyst retarded the rate of arsination.

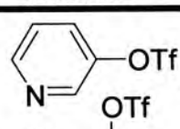
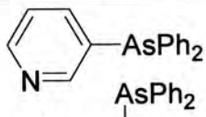
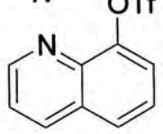
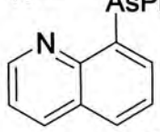
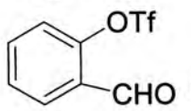
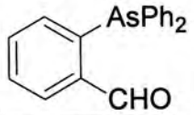
There are at least two different aspects in phosphination and arsination. Firstly, the rate of arsination of aryl triflates was much slower than that of phosphination. Presumably, triphenylarsine is less nucleophilic than triphenylphosphine such that the arsonium intermediate forms slower in rate (More details will be discussed in the mechanism section). Secondly, the nitro group was compatible in arsination but not in phosphination in which 4-bromonitrobenzene was reduced to 4-bromoaniline without any phosphination which was discussed in chapter 2.3 (eq 2.3.1).[39]



(2.3.1)

Limitations still exist in palladium catalyzed arsination. Heterocyclic aromatic substrates did not react at all. The strong coordination of pyridine nitrogen atom to palladium catalyst may inhibit the arsination reaction. Sterically more hindered *ortho*-formyl phenyl triflate did not react (Table 3.4.2).

Table 3.4.2 Unsuccessful palladium catalyzed arsination

Entry	Substrate	Product	Time / day	Yield / %
1	 **38**	 **85**	5	No desired product[a]
2[b]	 **39**	 **86**	5	No desired product[a]
3	 **84**	 **87**	5	No desired product[a]

[a] Starting material remained & unreacted.

[b] Temperature was increased to 140°C after 5 days reaction.

3.5 Mechanistic Studies of Arsination

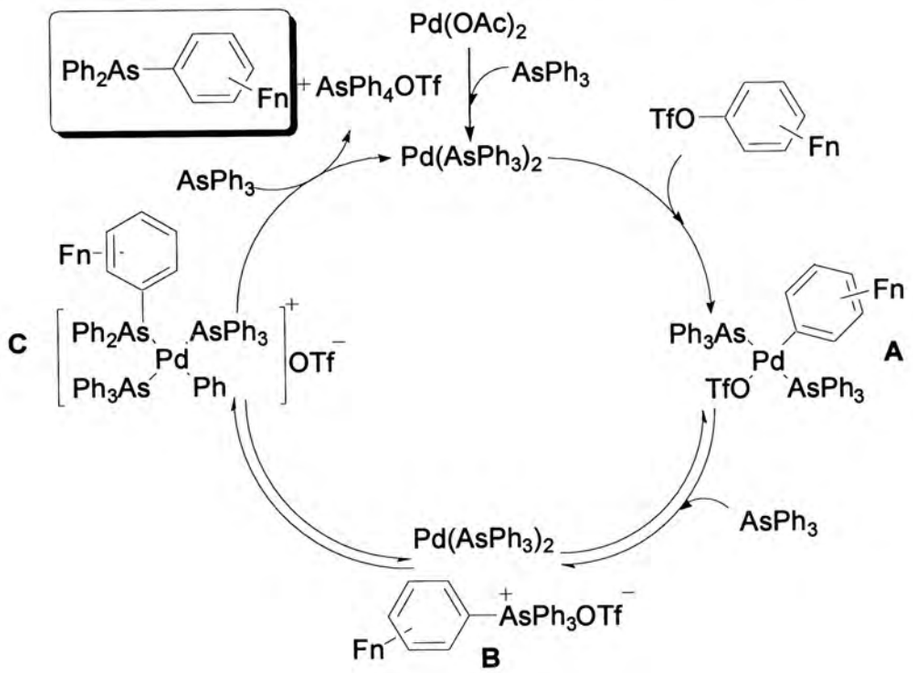
A proposed mechanism of the arsination starts with *in situ* reduction of $Pd(OAc)_2$ by triphenylarsine to Pd(0).[39] In fact, $Pd(OAc)_2$ reacted with triphenylarsine to yield triphenylarsine oxide in 67% yield (eq 3.5.1).

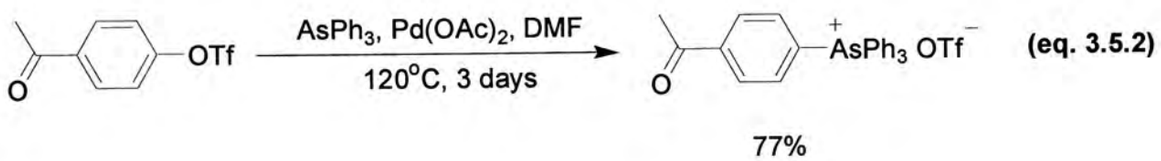
$$AsPh_3 + Pd(OAc)_2 \xrightarrow[3\ days]{110\ ^oC} \underset{63\%}{Ph_3As{=}O} + \underset{Not\ determined}{Pd(0)} + Ac_2O \qquad \textbf{(3.5.1)}$$

Then, oxidative addition of an aryl triflate with $Pd(AsPh_3)_n$ (n likely equals to 2) catalyst forms complex **A** (Scheme 3.5). Subsequent reductive elmination of **A** with triphenylarsine gives the arsonium salt **B** and Pd(0). Then **B** undergoes oxidative addition with the palladium(0) catalyst to generate the coordinated arsine product complex **C**. Finally, ligand substitution by a second equivalent of triphenylarsine regenerates the Pd(0) catalyst, substituted aryl arsine product and the side product arsonium salt which was isolated in 70% crude yield in the case of 4-(acetylphenyl)triphenylarsonium triflate and confirmed by mass spectrometric analysis (Scheme 3.5). The identity of 4-(acetylphenyl)triphenyl-arsonium triflate

was further confirmed by independent synthesis, and was prepared from the reaction of 1 equivalent triphenylarsine and 4-acetylphenyl triflate in the presence of $Pd(OAc)_2$ for 3 days in 77% yield (eq 3.5.2).

Scheme 3.5 Proposed mechanism of arsination





(eq. 3.5.2)

Chapter 4 Green Chemistry Approach – Solventless Phosphination and Arsination

4.1 Introduction to Green Chemistry

During the last decade, global environmental pollution and destruction have drawn much attention. In 1996, the Working Party on 'Synthetic Pathways and Processed in Green Chemistry' was established within the IUPAC Commission III.2 to pay more attention for an area of rapidly expanding research and development, defined as *'the invention, design and application of chemical products and processes to reduce or to eliminate the use and generation of hazardous substances'*.[45-47] The aim of green chemistry is to reduce the hazards associated with products and processes that are essential not only to maintain the quality of life but also to achieve further advance in technology. Nowadays, many chemists are developing new environmentally benign synthesis.

Metal catalysts are usually involved in oxidations of organic compounds. The control and treatment of metal catalysts require huge cost. Recently, metal catalysts are replaced by several metal-free oxidizing reagent such as ozone in order to minimize or eliminate the metal waste.[47]

In order to reduce the toxic chemical waste as well as organic solvents, Breslow and co-workers were the first research group to discover that water could be used in organic synthesis instead of organic solvent.[46] Since water is cheap, non-toxic, it is ideal for moisture-compatible reactions.

Recently, perfluorinated solvents and fluorobiphasic catalysis have drawn much attention.[48] Perfluorinated solvents are miscible with another organic solvents at high

temperature but become immiscible at low temperature. As these fluorinated solvents display low chemical reactivity, low toxicity, high density and biphasic properties,[49] they are therefore ideal solvents for fluorinated catalysts to catalyze organic reactions to allow easy separation of products from catalyst-recycling. However, the cost of synthesis of fluorinated catalyst is still high and further improvement needs to be made.

Supercritical fluids such as carbon dioxide are important kind of environmentally benign solvents. Supercritical carbon dioxide is non-toxic, inert and compatible with many reactions. Varieties of chemical reactions are tolerated in supercritical carbon dioxide such as catalyzed coupling reactions and hydroformylation.[45] High pressure system however is required.

In spite of these advances in solvents for green chemistry, the most direct approach seems to be the total elimination of the use of any solvent, i.e. solvent-free reaction. Furthermore, solvent-free reaction is not limited by the boiling points of solvents.[50]

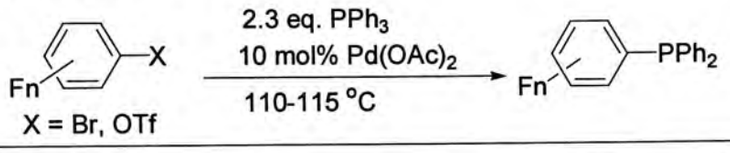
In order to develop a more user-friendly, economically attractive and environmentally benign phosphination and arsination, we initiated to investigate the possibility of carrying out the phosphination and arsination in solvent-free conditions.

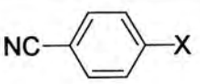
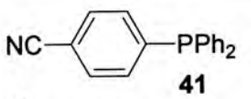
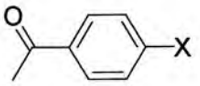
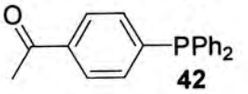
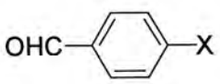
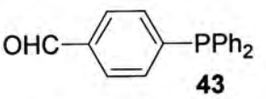
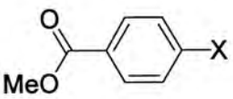
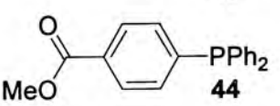
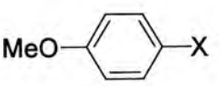
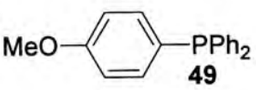
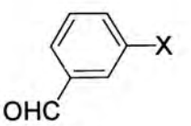
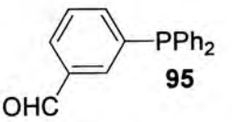
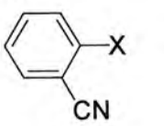
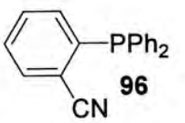
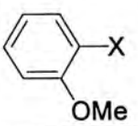
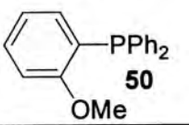
4.2 Results of solventless phosphination

The phosphination reactions were found to be successful in solvent-free conditions for aryl bromides, triflates and nonaflate in 1-3 days at 110-115°C and comparable yields were achieved with those obtained in DMF solvent (Table 4.2.1). Generally, the isolated yields of electron-poor phosphines were higher than those of electron-rich ones. Likely, electron-poor phosphines are more oxidation-stable and

less oxidized side-products formed during chromatography purification.

Table 4.2.1 Catalytic solvent-free phosphination of aryl bromides, triflates and nonaflate



Entry	Substrate	X		Product	Time/d	%Yield[a]
1		X = Br	**88**	 **41**	2.5	38
2		X = OTf	**22**		1.0	38
3		X = Br	**69**	 **42**	1.5	44
4		X = OTf	**23**		1.0	40
5		X = Br	**89**	 **43**	2.5	40
6		X = OTf	**25**		2.5	42
7[c]		X = Br	**90**	 **44**	2.5	40
8		X = OTf	**26**		1.5	42
9[c]		X = ONf	**75**		1.5	43
10		X = Br	**91**	 **49**	1.0	33
11[c]		X = OTf	**33**		0.8	26
12		X = Br	**92**	 **95**	2.5	34
13[c]		X = OTf	**73**		1.5	38
14		X = Br	**93**	 **96**	7.0	no rxn[b]
15[c]		X = OTf	**74**		2.5	37
16		X = Br	**94**	 **50**	7.0	no rxn[b]
17[c]		X = OTf	**35**		3.5	27

[a] Isolated yields were reported.

[b] Starting material was not consumed.

[c] Dr. Fuk Yee Kwong's preliminary result.

No significant electronic effect was observed in the solvent-free phosphination since both electron withdrawing and donating substrates exhibited similar reaction rate. Aryl triflates and nonaflates underwent faster reactions than aryl bromides as they are better leaving groups. Moreover, the oxidative addition of aryl triflates and phosphonium salts by palladium catalyst are likely more facile than that of aryl

bromides. *ortho*-Substituted aryl bromides still did not react in solventless palladium catalyzed phosphination even at 140 °C for 7 days (Table 4.2.1, entry 14, 16).

The rates of the reactions in solvent-free conditions were slower than that in DMF. Presumably, the high viscosity of the reaction mixture was responsible. As the melting point of PPh_3 is 79 °C and the reaction temperature was at 110-115 °C, triphenylphosphine behaved as the solvent, ligand and phosphinating agent.

4.3 Result of solventless arsination

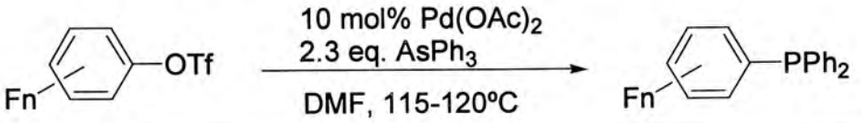
Likewise, palladium catalyzed arsination was also successful in solvent-free conditions in 3 to 5 days at 120 °C to give moderate yields of products. The rates of reactions and the yields of products were nearly the same as those in DMF (Table 4.3.1). In contrast to phosphination, substituent electronic effect on aryl triflates had little effect on the yield in arsination.

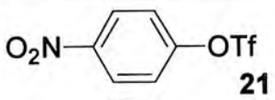
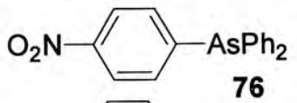
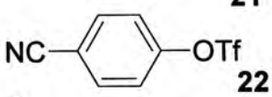
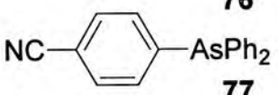
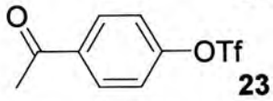
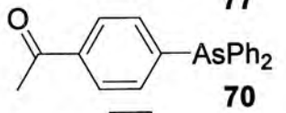
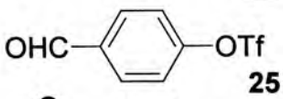
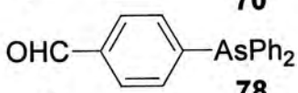
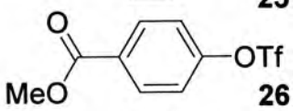
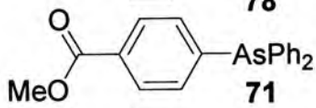
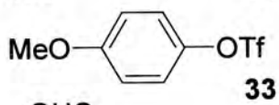
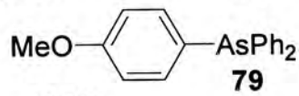
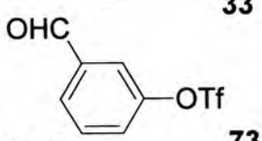
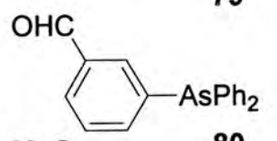
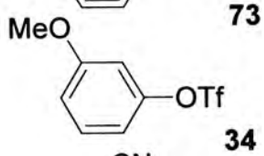
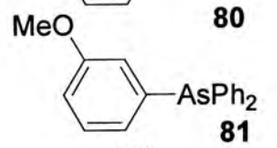
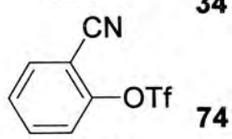
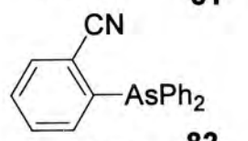
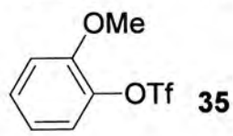
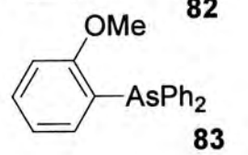
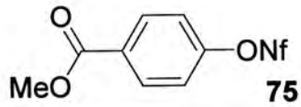
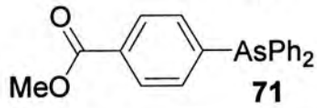
There was a little difference between the rate of reaction in DMF or solvent-free conditions. As triphenylarsine melts at 60°C, at 120°C it behaved as the solvent, ligands and arsinating agent.

In order to understand more about the physical state of the reaction, mixed melting point experiments were carried out. Though there are many reports on solid-state reactions, catalytic solid-state reactions are less common since the diffusion of the catalyst in solid is expected to be difficult. According to the proposed mechanism (Scheme 3.5.1), a mixture of arsonium salt intermediate and product was formed during the reaction. From the mixed melting point experiments, the reaction medium was likely to be in the partial molten state even though the melting points of the specified mixture were higher than 120°C (Figure 4.3). More importantly, triphenylarsine and aryldiphenylarsine melt well below 120°C and acted as the

solvent.

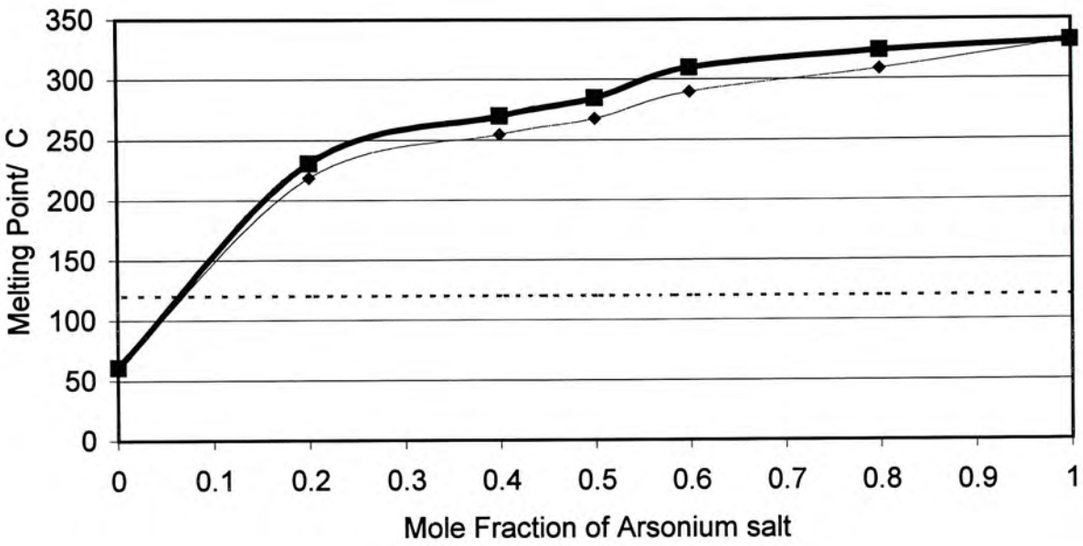
Table 4.3.1 Solventless palladium catalyzed arsination of aryl triflates and nonaflates



Entry	Substrates	Products	Time/h	% Yield[a]
1	 **21**	 **76**	5	40
2	 **22**	 **77**	5	51
3	 **23**	 **70**	4	47
4	 **25**	 **78**	5	50
5	 **26**	 **71**	5	51
6	 **33**	 **79**	4.5	50
7	 **73**	 **80**	5	48
8	 **34**	 **81**	4	45
9	 **74**	 **82**	5	41
10	 **35**	 **83**	5	49
11	 **75**	 **71**	4	50

[a] Isolated yield was reported.

Figure 4.3 Melting Point of the Mixture of 4-Acetylphenyl-triphenylarsonium Triflate and Triphenylarsine



In conclusion, user-friendly, economically attractive and environmentally friendly solvent-free palladium catalyzed arsination and phosphination have been developed. The yields and rates are comparable with those in DMF.

Conclusion

A novel palladium catalyzed phosphination of aryl triflates was successfully developed. This convenient synthetic protocol tolerated aldehyde, ketone, ester, nitrile, pyridyl, methyl ether and halide functional groups.

Palladium catalyzed arsination of aryl triflates was also successfully developed. The methodology tolerates aldehyde, ester, ketone, nitro, nitrile, and methyl ether.

Both phosphination and arsination can be carried out in the absence of solvent.

Experimental Section

Unless otherwise noted, all reagents were purchased from commercial suppliers and used without purification. Dichloromethane for the reaction were distilled from calcium hydride. Hexane for chromatography was distilled from anhydrous calcium chloride, Tetrahydrofuran (THF) and diethyl ether were distilled from sodium and benzophenone ketyl prior to use, *N,N*-dimethylformamide (DMF) was distilled from magnesium sulfate under reduced pressure. Thin layer chromatography was performed on pre-coated silica gel 60 F_{254} plated. Silica gel (Merch, 70-230 and 230-400 mesh) was used for column chromatography.

^{1}H NMR spectra were recorded on a Brüker DPX 300 (300MHz) spectrometer. Spectra were referenced internally to the residual proton resonance in $CDCl_3$ (δ 7.26 ppm), or with tetramethylsilane (TMS, δ 0.00 ppm) as the internal standard. Chemical shifts (δ) were reported as part per million (ppm) in δ scale downfield from TMS. ^{13}C NMR spectra were recorded on a Brüker DPX 300 (75 MHz) spectrometer and referenced to $CDCl_3$ Spectra were referenced (δ 77.00 ppm). ^{31}P NMR spectra were recorded on Varian 400 (162 MHz) and referenced to 85% H_3PO_4 externally. Coupling constants (*J*) were reported in Hertz (Hz). Mass spectra (EIMS and FABMS) were recorded on a HP 5989B Mass Spectrometer. High resolution mass spectra (HRMS) were performed on a Brüker APEX 47e FT-ICR mass spectrometer (ESIMS). GC-MS analysis was conducted on a HP G1800C GCD system using a HP5MS column (30m x 0.25mm x 0.25μm), temperature programming: 70-210°C, 7 min; 210°C, 1 min; 210-280°C, 7 min; 280°C, 1 min.

General Procedure for Trifluoromethanesulfonation of Phenols

4-Nitrophenyltrifluoromethanesulfonate (21).[51] 4-Nitrophenol **(1)** (0.5 g, 3.6 mmol) was dissolved in dry dichloromethane (20 mL) under nitrogen at room temperature followed by the addition of dry pyridine (0.87 mL, 10.8 mmol). Trifluoromethanesulfonic anhydride (triflic anhydride) (0.67 mL, 4.0 mmol) in dry dichloromethane (10 mL) was then added dropwisely. The color of the solution was changed from yellow to orange with white fume evolved. The reaction mixture was allowed to stir at room temperature for an hour. Water (20 mL) was then added and the reaction mixture was extracted with dichloromethane (3 x 15 mL). The combined organic phase was washed with diluted hydrochloric acid, water, brine and dried over $MgSO_4$. The residue after rotary evaporation was purified by column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 3:1) as the eluent to obtain the 4-nitrophenyltrifluoromethanesulfonate **(21)** (878 mg, 90%) as a pale yellow solid. R_f= 0.7 (hexane/ethyl acetate = 3 : 1); Mp = 52-54°C (Lit[51] 52-55°C); ^{1}H NMR (300 MHz, CDC_{l3}) δ 7.47 (dd, 2 H, J = 1.4, 7.8 Hz), 8.37 (dd, 2 H, J = 1.4, 7.9 Hz); MS (EI): m/z (relative intensity) 271 (M^+, 100), 255 (17), 225 (40), 138 (67).

4-Cyanophenyltrifluoromethanesulfonate (22)[35]**.** The general procedure for synthesis of aryl triflate for compound **21** was used. 4-Cyanophenol **(2)** (0.71 g, 6.0 mmol), pyridine (1.5 mL, 18.0 mmol), triflic anhydride (1.1 mL, 6.6 mmol) and dry dichloromethane (20 mL) were used to afford 4-cyanophenyl-trifluoromethanesulfonate **(21)** (1.4 g, 96%) as a colorless oil. R_f = 0.6 (hexane/ethyl acetate = 3:1); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.45 (dd, 2 H, J = 8.7, 12.0 Hz), 7.12 (dd, 2 H, J = 8.6, 12.0 Hz); MS (EI): *m/z* (relative intensity) 251 (M^+, 44), 211 (100), 173 (28).

4-Acetylphenyltrifluoromethanesulfonate (23).[35] The general procedure for synthesis of aryl triflate for compound **21** was used. 4-Hydroxyacetophenone **(3)** (2.7 g, 20.0 mmol), pyridine (4.8 mL, 40.0 mmol), triflic anhydride (3.7 mL, 22.0 mmol) and dry CH_2Cl_2 were used to yield 4-acetylphenyltrifluoromethanesulfonate **(21)** (4.6 g, 87%) as a colorless liquid. R_f= 0.41 (hexane/ethyl acetate = 5:1); ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.65 (s, 3 H), 7.43 (d, 2 H, J = 8.7 Hz), 8.00 (d, 2 H, J = 8.4 Hz). MS (EI): m/z (relative intensity) 268 (M^+, 48), 189 (100), 161 (42).

2-Acetylphenyltrifluoromethanesulfonate (24).[37] The general procedure for synthesis of aryl triflate for compound **21** was used. 2-Hydroxyacetophenone **(4)** (1.4 g, 10.0 mmol), pyridine (2.4 ml, 30.0 mmol), triflic anhydride (1.9 ml, 1.9 mmol) and dry CH_2Cl_2 (20 ml) were used to yield 2-acetylphenyltrifluoromethanesulfonate **(24)** (557 mg, 58%) as a colorless liquid. R_f= 0.62 (hexane/ethyl acetate = 5:1); ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.62 (s, 3 H), 6.86-6.98 (m, 2 H), 7.43-7.49 (m, 1 H), 7.72 (dd, 1 H, J = 1.5, 8.1 Hz). MS (EI): m/z (relative intensity) 268 (M^+, 40), 201 (100), 173 (30).

4-Trifluoromethanesulfonyloxybenzaldehyde (25).[35] The general procedure for synthesis of aryl triflate for compound **21** was used. 4-Hydroxybenzaldehyde **(5)** (732 mg, 6.0 mmol), pyridine (1.5 mL, 18.0 mmol), triflic anhydride (1.1 ml, 6.6 mmol) and dry CH_2Cl_2 (15 ml) were used to yield 4-trifluoromethane-sulfonyloxybenzaldehyde **(25)** (944 mg, 85%) as a colorless liquid. R_f = 0.5 (hexane/ethyl acetate = 4:1); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.44 (d, 2 H, J = 8.7 Hz), 7.99 (d, 2 H, J = 8.4 Hz), 10.03 (s, 1 H). MS (EI): m/z (relative intensity) 254 (M^+, 80), 189 (100), 161 (12).

Methyl 4-trifluoromethanesulfonyloxybenzoate (26).[35] The general procedure for synthesis of aryl triflate for compound **21** was used. Methyl 4-hydroxybenzoate **(6)** (913 mg, 6 mmol), pyridine (1.5 ml, 18.0 mmol), triflic anhydride (1.1 ml, 6.6 mmol) and dry CH_2Cl_2 (20 ml) were used to yield methyl 4-trifluoromethanesulfonyloxybenzoate **(26)** (1.6 g, 91%) as a colorless liquid. R_f= 0.52 (hexane/ethyl acetate = 5:1); ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.92 (s, 3 H), 7.34 (dt, 2 H, *J* = 2.4, 9.0 Hz), 8.13 (dt, 2 H, *J* = 2.3, 9.0 Hz). MS (EI): m/z (relative intensity) 284 (M^+, 46), 253 (77), 189 (100), 161 (17).

4-Chlorophenyltrifluoromethanesulfonate (27).[37] The general procedure for synthesis of aryl triflate for compound **21** was used. 4-Chlorophenol **(7)** (0.64 g, 5.0 mmol), pyridine (1.2 mL, 15.0 mmol), triflic anhydride (0.87 mL, 5.2 mmol) and dry CH_2Cl_2 (20 ml) were used to yield 4-chlorophenyltrifluoromethanesulfonate **(27)** (1.21, 93%) as a colorless oil. R_f = 0.3 (hexane); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.28 (dd, 2 H, *J* = 8.7, 12.0 Hz), 7.64 (dd, 2 H, *J* = 8.6, 12.0 Hz); MS (EI): *m/z* (relative intensity) 262 (M^+, 80), 260 (27), 225 (33), 127 (66).

4-Bromophenyltrifluoromethanesulfonate (28).[37] The general procedure for synthesis of aryl triflate for compound **21** was used. 4-Bromophenol **(8)** (0.52 g, 3.0 mmol), pyridine (0.8 mL), triflic anhydride (0.55 mL, 3.3 mmol) and dry dichloromethane (8 mL) were used to afford the 4-bromophenyltrifluoro-methanesulfonate **(28)** (832 mg, 91%) as a colorless oil. R_f = 0.8 (hexane/ethyl acetate = 10:1); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.27 (dd, 2 H, *J* = 8.7, 12.0 Hz), 7.62 (dd, 2 H, *J* = 8.6, 12.0 Hz); MS (EI): *m/z* (relative intensity) 306 (M^+, 100), 304 (95), 225 (44), 173 (28), 171 (22).

4-Tolyltrifluoromethanesulfonate (29).[37] The general procedure for synthesis of aryl triflate for compound **21** was used. 4-Methylphenol **(9)** (216 mg, 2.0 mmol), pyridine (0.48 ml, 6.0 mmol), triflic anhydride (0.37 ml, 2.2 mmol) and dry CH_2Cl_2 (20 ml) were used to yield 4-tolyltrifluoromethanesulfonate **(29)** (2.14 mg, 89%) as a pale yellow liquid. R_f= 0.49 (hexane/ethyl acetate = 5:1); ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.48 (s, 3 H), 7.26 (d, 2 H, *J* = 8.7 Hz), 7.34 (d, 2 H, *J* = 8.7 Hz). MS (EI): *m/z* (relative intensity) 240 (M^+, 33), 201 (50), 161 (27), 133 (49), 69 (100).

2-Tolyltrifluoromethanesulfonate (30).[37] The general procedure for synthesis of aryl triflate for compound **21** was used. 2-Methylphenol **(10)** (216 mg, 2.0 mmol), pyridine (0.48 ml, 6.0 mmol), triflic anhydride (0.37 ml, 2.2 mmol) and dry CH_2Cl_2 (15 ml) were used to yield 2-tolyltrifluoromethanesulfonate **(30)** (442 mg, 92%) as a pale yellow liquid. R_f= 0.31 (hexane/ethyl acetate = 3:1); ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.37 (s, 3 H), 7.25-7.31 (m, 4 H). MS (EI): m/z (relative intensity) 240 (M^+, 23), 183 (39), 104 (100).

4-*tert*-Butylphenyltrifluoromethanesulfonate (31)[52] The general procedure for synthesis of aryl triflate for compound **21** was used. 4-*tert*-Butylphenol **11** (0.75 g, 5.0 mmol), pyridine (1.2 mL, 15.0 mmol), triflic anhydride (0.87 mL, 5.2 mmol) and dry CH_2Cl_2 (20 ml) were used to yield 4-*tert*-butylphenyltrifluoromethanesulfonate **(31)** (1.3 g, 90%) as a colorless oil. R_f = 0.5 (hexane); ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.33 (s, 9 H), 7.18 (dd, 2 H, *J* = 8.7, 12.1 Hz), 7.44 (dd, 2 H, *J* = 8.6, 12.0 Hz); MS (EI): *m/z* (relative intensity) 282 (M^+, 100), 225 (67), 149 (55).

2,4-Di*tert*-butylphenyltrifluoromethanesulfonate (32).[37] The general procedure for synthesis of aryl triflate for compound **21** was used. 2,4-Di-*tert*-butylphenol **(12)** (1.0 g, 5.0 mmol), pyridine (1.2 ml, 15.0 mmol), triflic anhydride (0.93 ml, 5.5 mmol) and dry CH_2Cl_2 (20 ml) were used to yield 2,4-di-*tert*-butylphenyltrifluoromethanesulfonate **(32)** (1.49 g, 88%) as a white solid. R_f = 0.84 (hexane/ethyl acetate = 10:1); Mp = 56-58°C (Lit[37] 56-57°C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.32 (s, 9 H), 1.43 (s, 9 H), 7.26-7.46 (m, 3 H). MS (EI): m/z (relative intensity) 338 (M^+, 25), 293 (19), 248 (100), 161 (17), 133 (49).

4-Methoxyphenyltrifluoromethanesulfonate (33).[37] The general procedure for synthesis of aryl triflate for compound **21** was used. 4-Methoxyphenol **(13)** (248 mg, 2.0 mmol), pyridine (0.48 ml, 6.0 mmol), triflic anhydride (0.37 ml, 2.2 mmol) and dry CH_2Cl_2 (15 ml) were used to yield 4-methoxyphenyltrifluoromethanesulfonate **(33)** (450 mg, 88%) as a pale yellow liquid. R_f = 0.56 (hexane/ethyl acetate = 5:1); ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.80 (s, 3 H), 6.91 (d, 2 H, J = 9.0 Hz), 7.18 (d, 2 H, J = 9.3 Hz), 7.28-7.31 (m, 1 H). MS (EI): m/z (relative intensity) 254 (M^+, 33), 215 (11), 161 (17), 133 (49), 69 (100).

3-Methoxyphenyltrifluoromethanesulfonate (34).[37] The general procedure for synthesis of aryl triflate for compound **21** was used. 3-Methoxyphenol **(14)** (1.24 g, 10.0 mmol), pyridine (1.5 ml, 30.0 mmol), triflic anhydride (1.9 ml, 11.0 mmol) and dry CH_2Cl_2 (20 ml) were used to yield 3-methoxyphenyltrifluoromethanesulfonate **(34)** (2.3 g, 88%). as a pale yellow liquid. R_f = 0.45 (hexane/ethyl acetate = 10:1); ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.90 (s, 3 H), 6.96-7.04 (m, 2 H), 7.19-7.22 (m, 1 H),

7.28-7.31 (m, 1 H). MS (EI): *m/z* (relative intensity) 256 (M^+, 50), 123 (100), 95 (60), 77 (37).

2-Methoxyphenyltrifluoromethanesulfonate (35).[37] The general procedure for synthesis of aryl triflate for compound **21** was used. 2-Methoxyphenol **(15)** (1.1 g, 10.0 mmol), pyridine (2.4 ml, 20.0 mmol), triflic anhydride (1.9 ml, 11.0 mmol) and dry CH_2Cl_2 (20 ml) were used to yield 2-methoxyphenyltrifluoromethanesulfonate **(35)** (2.1 g, 82%) as a colorless liquid. R_f = 0.54 (hexane/ethyl acetate = 10:1); ^1H NMR (300 MHz, $CDCl_3$) δ 6.80 (t, 1 H, J = 2.4 Hz), 6.85-6.95 (m, 2 H), 7.35 (t, 1 H, J = 8.3 Hz). MS (EI): m/z (relative intensity) 256 (M^+, 27), 209 (58), 108 (100).

1-Naphthyltrifluoromethanesulfonate (36).[37] The general procedure for synthesis of aryl triflate for compound **21** was used. 1-Naphthol **(16)** (288 mg, 2.0 mmol), pyridine (0.5 mL, 6.0 mmol), triflic anhydride (0.4 mL, 2.1 mmol) and dry dichloromethane (30 mL) were used to yield the 1-naphthyltrifluoromethansulfonate **(36)** (928 mg, 79%) as a white solid. R_f = 0.58 (hexane/ethyl acetate = 5:1); Mp = 30-32°C (Lit[37] 30-32°C); ^1H NMR (300 MHz, $CDCl_3$) δ 7.87 (dd, 1 H, J = 1.3, 7.8 Hz), 7.64 (d, 1 H, J = 7.8 Hz), 7.32-7.55 (m, 5 H); MS (EI): *m/z* (relative intensity) 276 (M^+, 100), 143 (74).

2-Naphthyltrifluoromethanesulfonate (37).[37] The general procedure for synthesis of aryl triflate for compound **21** was used. 2-Naphthol **(17)** (577 mg, 4.0 mmol), pyridine (1 mL, 12.0 mmol), triflic anhydride (0.7 mL, 4.2 mmol) and dry dichloromethane (30 mL) were used to yield the 2-naphthyltrifluoromethansulfonate **(37)** (928 mg, 92%) as a colorless liquid. R_f = 0.6 (hexane/ethyl acetate = 4:1); ^1H

NMR (300 MHz, $CDCl_3$) δ 7.63 (dd, 1 H, J = 1.3, 7.8 Hz), 7.59 (d, 1 H, J = 7.9 Hz), 7.32-7.55 (m, 5 H); MS (EI): *m/z* (relative intensity) 276 (M^+, 100), 143 (86).

3-Pyridyltrifluoromethanesulfonate (38).[53] 3-Hydroxypyridine **(18)** (0.5 g, 5.3 mmol) was dissolved in anhydrous dichloromethane (10 mL) under nitrogen at room temperature followed by the addition of dry pyridine (1.3 mL, 15.9 mmol). Triflic anhydride (0.98 mL, 5.8 mmol) in dichloromethane (3 mL) was then added dropwisely. The color of the solution was changed from orange to red with white fume evolved. The reaction mixture was allowed to stir at room temperature for one hour. Water (20 mL) was added, extracted with dichloromethane (3 x 30 mL). The combined organic phase was washed with water, brine and dried over $MgSO_4$. The residue was purified by short column chromatography on silica gel to afford the 3-pyridyltrifluoromethanesulfonate **(38)** (1.08 g, 90%) as a pale yellow oil. R_f = 0.3 (hexane/ethyl acetate = 3:1); ^1H NMR (300 MHz, $CDCl_3$) δ 8.52 (d, 1 H, J = 1.5 Hz), 8.43 (d, 1 H, J = 8.0 Hz), 7.66 (t, 1 H, J = 8.0 Hz), 7.35 (d, 1 H, J = 7.9 Hz); MS (EI): *m/z* (relative intensity) 227 (M^+, 100), 158 (10), 94 (70).

8-Quinonyltrifluoromethanesulfonate (39).[54] The general procedure of trifluoromethanesulfonation for compound **38** was used. 8-Hydroxylquinoline **(19)** (0.5 g, 3.5 mmol), pyridine (0.83 mL, 10.4 mmol), triflic anhydride (0.64 mL, 3.8 mmol) and dry dichlromethane (20 mL) were used to afford the 8-quinonyltrifluoromethanesulfonate **(39)** (878 mg, 92%) as a pale yellow solid. R_f = 0.4 (hexane/ethyl acetate = 3:1); Mp = 70-73°C (Lit[54] 70-72°C); ^1H NMR (300 MHz, $CDCl_3$) δ 8.50 (d, 1 H, J = 1.5 Hz), 7.87 (d, 1 H, J = 8.1 Hz), 7.34-7.67 (m, 4 H); MS (EI): *m/z* (relative intensity) 277 (M^+, 100), 144 (54).

1,4-Ditrifluoromethanesulfonyloxybenzene (40).[37] The general procedure for synthesis of aryl triflate for compound **21** was used. 1,4-Dihydroxybenzene **(20)** (550 mg, 5.0 mmol), pyridine (2.4 ml, 30.0 mmol), triflic anhydride (2 ml, 12.0 mmol) and dry CH_2Cl_2 (20 ml) were used to yield 1,4-ditrifluoromethanesulfonyloxybenzene **(40)** (1.8 g, 95 %) as a white solid. After purified by column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 5:1) as the eluent. R_f = 0.74 (hexane/ethyl acetate = 5:1); Mp = 53-55°C (Lit[37] 52-55°C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.4 (s, 4 H). MS (EI): m/z (relative intensity) 374 (M^+, 43), 189 (100), 133 (49).

General Procedure for Palladium Catalyzed Phosphination *(Methods A)* and Solvent-free Palladium Catalyzed Phosphination *(Methods B)*

4-(Diphenylphosphino)benzonitrile (41).[55] *Method A:* 4-Cyanophenyltrifluoro-methanesulfonate **(22)** (251 mg, 1.0 mmol), palladium(II) acetate (22.4 mg, 0.1 mmol), triphenylphosphine (603 mg, 2.3 mmol) were dissolved in DMF (2 mL) in a Teflon screw-capped flask under nitrogen. The reaction mixture was heated to 110-115°C for 2 hours and the color of the solution was changed from pale yellow to red. 4-(Diphenylphosphino)benzonitrile **(41)** was obtained (108 mg, 38%) as a white solid after purified by column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 10 : 1) as the eluent. R_f = 0.6 (hexane/ethyl acetate = 10 : 1); Mp = 120-122°C (Lit[55] 120-122°C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.28-7.39 (m, 12 H), 7.57 (dd, 2 H, J = 1.2, 8.4 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 111.8, 118.9, 128.8 (d, J_{CP} = 7.4 Hz), 129.5, 131.7 (d, J_{CP} = 5.9 Hz), 133.4 (d, J_{CP} = 18.4 Hz), 134.0 (d, J_{CP} = 20.2 Hz), 135.3 (d, J_{CP} = 10.3 Hz), 145.1 (d, J_{CP} = 16.5 Hz); MS (EI): *m/z* (relative intensity) 287 (M^+, 100), 208 (55), 195 (8), 183 (62), 177 (12). *Method B:* 4-

Bromobenzonitrile **(88)** (185 mg, 1.0 mmol), palladium(II) acetate (22.4 mg, 0.1 mmol) and triphenylphosphine (603 mg, 2.3 mmol) were mixed in a Teflon screw-capped flask under nitrogen. The reaction mixture was heated to 110-115°C to yield 4-(diphenylphosphino)benzonitrile **(41)** (109 mg, 38%) as a white solid. *Method C:* 4-Cyanophenyltrifluoromethanesulfonate **(22)** (151 mg, 0.5 mmol), palladium(II) acetate (11.2 mg, 0.05 mmol) and triphenylphosphine (301 mg, 1.15 mmol) were mixed in a Teflon screw-capped flask under nitrogen. The reaction mixture was heated to 110-115°C to yield 4-(diphenylphosphino)benzonitrile **(41)** (55 mg, 38%) as a white solid.

4-(Diphenylphosphino)acetophenone (42).[56] *Method A:* 4-Acetylphenyltriflate **(23)** (134 mg, 0.5 mmol), palladium(II) acetate (11.2 mg, 0.05 mmol), triphenylphosphine (301 mg, 1.15 mmol) and DMF (2 mL) were used to yield 4-(Diphenylphosphino)acetophenone **(42)** (56 mg, 37%) as a white solid. R_f = 0.3 (hexane/ethyl acetate = 15 : 1); Mp = 115-118°C (Lit[56] 115-116°C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.57 (s, 3 H), 7.29-7.38 (m, 12 H), 7.88 (dd, 2 H, J = 1.3, 8.3 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 26.6, 127.9 (d, J_{CP} = 6.2 Hz), 128.6 (d, J_{CP} = 7.2 Hz), 129.1, 133.2 (d, J_{CP} = 18.5 Hz), 133.9 (d, J_{CP} = 19.9 Hz), 135.9 (d, J_{CP} = 10.4 Hz), 136.7, 144.3 (d, J_{CP} = 14.2 Hz), 197.8; MS (EI): *m/z* (relative intensity) 304 (M^+, 100), 289 (10), 261 (12), 227 (11), 183 (90), 152 (30). *Method B:* 4-Bromoacetophenone **(69)** (199 mg, 1.0 mmol), palladium(II) acetate (22.4 mg, 0.1 mmol) and triphenylphosphine (602 mg, 2.3 mmol) to yield 4-(diphenylphosphino)-acetophenone **(42)** (135 mg, 37%) as a white solid. *Method C:* 4-Acetylphenyltriflate **(23)** (268 mg, 1.0 mmol), palladium(II) acetate (22.4 mg, 0.1 mmol) and

triphenylphosphine (602 mg, 2.3 mmol) were used to yield 4-(diphenylphosphino)acetophenone (**42**) (122 mg, 40%) as a white solid.

4-(Diphenylphosphino)benzaldehyde (43).[57] *Method A:* 4-Trifluoromethane-sulfonyloxybenzaldehyde **(25)** (127 mg, 0.5 mmol), palladium(II) acetate (11.2 mg, 0.05 mmol), triphenylphosphine (301 mg, 1.15 mmol) and dry DMF (2 mL) were used to yield the 4-(diphenylphosphino)benzaldehyde **(43)** (45 mg, 31%) as a white solid. R_f = 0.6 (hexane/ethyl acetate = 10 : 1); Mp = 109-111°C (Lit[57] 109-112°C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.32-7.43 (m, 12 H), 7.80 (dd, 2 H, J = 1.5, 8.1 Hz), 10.00 (s, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 128.8 (d, J_{CP} = 7.2 Hz), 129.3, 133.5 (d, J_{CP} = 18.3 Hz), 134.0 (d, J_{CP} = 20.0 Hz), 135.7 (d, J_{CP} = 10.4 Hz), 136.0, 146.5 (d, J_{CP} = 15.5 Hz), 191.9; ^{31}P (162 MHz, $CDCl_3$) δ -3.41; MS (EI): *m/z* (relative intensity) 290 (M^+, 100), 261 (8), 211 (9), 183 (95), 165 (12), 152 (20). *Method B:* 4-Bromobenzoaldehyde **(89)** (185 mg, 1.0 mmol), palladium(II) acetate (22.4 mg, 0.1 mmol) and triphenylphosphine (602 mg, 2.3 mmol) were used to yield the 4-(diphenylphosphino)benzaldehyde **(43)** (117 mg, 40%) as a white solid. *Method C:* 4-Trifluoromethanesulfonyloxybenzaldehyde **(25)** (127 mg, 0.5 mmol), palladium(II) acetate (11.2 mg, 0.05 mmol) and triphenylphosphine (301 mg, 1.15 mmol) were used to yield the 4-(diphenylphosphino)benzaldehyde **(43)** (61 mg, 42%) as a white solid.

Methyl 4-(diphenylphosphino)benzoate (44).[58] Methyl 4-trifluoromethane-sulfonyloxybenzoate **(26)** (142 mg, 0.5 mmol), palladium(II) acetate (11.2 mg, 0.05 mmol), triphenylphosphine (301 mg, 1.15 mmol) and dry DMF (2 mL) were used to yield methyl 4-(diphenylphosphino)benzoate **(44)** (47 mg, 30%) as a white solid after purified by column chromatography on silica gel using a solvent mixture

(hexane/ethyl acetate = 10 : 1) as the eluent. R_f = 0.6 (hexane/ethyl acetate = 10 : 1); Mp = 105-107°C (Lit[58] 105-107°C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.28-7.38 (m, 12 H), 7.97 (dd, 2 H, J = 1.5, 8.4 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 52.2, 128.7 (d, J_{CP} = 7.1 Hz), 129.1, 129.3 (d, J_{CP} = 6.4 Hz), 133.0, 133.1 (d, J_{CP} = 18.5), 133.9 (d, J_{CP} = 19.9 Hz), 136.1 (d, J_{CP} = 10.5 Hz), 144.0 (d, J_{CP} = 14.0 Hz), 166.9; MS (EI): *m/z* (relative intensity) 320 (M^+, 100), 289 (8), 261 (7), 207 (9), 183 (70), 166 (12). *Method B:* Methyl 4-trifluoromethanesulfonyloxybenzoate **(26)** (142 mg, 0.5 mmol), palladium(II) acetate (11.2 mg, 0.05 mmol) and triphenylphosphine (301 mg, 1.15 mmol) were used to yield methyl 4-(diphenylphosphino)benzoate **(44)** (68 mg, 42%). R_f = 0.6 (hexane/ethyl acetate = 10 : 1) as a white solid. *Method C:* Methyl 4-bromobenzoate **(90)** (108 mg, 0.5 mmol), palladium(II) acetate (11.2 mg, 0.05 mmol) and triphenylphosphine (301 mg, 1.15 mmol) were used to yield methyl 4-(diphenylphosphino)benzoate **(44)** (64 mg, 40%) as a white solid.

1-(Diphenylphosphino)-4-chlorobenzene (45).[59] 4-Chlorophenyltrifluoromethane-sulfonate **(27)** (130 mg, 0.5 mmol), palladium(II) acetate (11.2 mg, 0.05 mmol), triphenylphosphine (301 mg, 1.15 mmol), anthracene (internal standard) (89 mg, 0.5 mmol), and DMF (2 mL) were used to yield the 1-(diphenylphosphino)-4-chlorobenzene **(45)** (45% GC yield), and the yield was determined by GC with respected to the calibration curve of the authentic sample and anthracene. Mp = 89-93°C (Lit[59] 88-90°C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.26-7.75 (m, 12 H), 7.83 (d, 2 H, J = 8.3 Hz); MS (EI): *m/z* (relative intensity) 298 (M^+, 20), 296 (90), 261 (100), 85 (10).

4-(Diphenylphosphino)toluene (46).[59] 4-tolyltrifluoromethanesulfonate **(29)** (120 mg, 0.5 mmol), palladium(II) acetate (11 mg, 0.05 mmol), triphenylphosphine (301 mg, 1.2 mmol) and internal standard anthracene (89 mg, 0.5 mmol) were dissolved in DMF (2 mL) in a Telfon screw-capped flask under nitrogen. The reaction mixture was heated to 110-115°C for 6 hours and the color of the solution was changed from pale yellow to orange. The reaction was cooled down and the yield of 4-(diphenylphosphino)toluene **(46)** (45% GC yield) was determined by GC with respected to the calibration curve of the authentic sample and anthracene. Mp = 78-80°C (Lit[59] 80-82°C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.39 (s, 3 H), 6.98 (d, 2 H, J = 8.2 Hz), 7.22-7.68 (m, *12* H); MS (EI): *m/z* (relative intensity) 275 (M^+, 100), 211 (24), 198 (56).

2-(Diphenylphosphino)toluene (47).[59] 2-Tolyltrifluoromethanesulfonate **(30)** (120 mg, 0.5 mmol), palladium(II) acetate (11 mg, 0.05 mmol), triphenylphosphine (301 mg, 1.2 mmol) and internal standard anthracene (89 mg, 0.5 mmol) were dissolved in DMF (2 mL) in a Telfon screw-capped flask under nitrogen. The reaction mixture was heated to 110-115°C for 6 hours and the color of the solution was changed from pale yellow to orange. The reaction was cooled down and the yield of 2-(diphenylphosphino)toluene **(47)** (67% GC yield) was determined by GC with respected to the calibration curve of the authentic sample and anthracene. Mp = 75-77°C (Lit[59] 76-78°C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.38 (s, 3 H), 6.95 (d, 2 H, J = 8.2 Hz), 7.22-7.60 (m, *12* H); MS (EI): *m/z* (relative intensity) 275 (M^+, 100), 212 (50), 198 (10).

1-(Diphenylphosphino)-4-*tert*-butylbenzene (48).[60] 4-*tert*-Butylphenyltrifluoromethanesulfonate **(31)** (141 mg, 0.5 mmol), palladium(II) acetate (11.2 mg, 0.05 mmol), triphenylphosphine (301 mg, 1.15 mmol) and internal standard anthracene (89 mg, 0.5 mmol) were dissolved in DMF (2 mL) in a Telfon screw-capped flask under nitrogen. The reaction mixture was heated to 110-115°C for 6 hours and the color of the solution was changed from pale yellow to orange. The reaction was cooled down and the yield of 1-(diphenylphosphino)-4-*tert*-butylbenzene **(48)** (50% GC yield) was determined by GC with respected to the calibration curve of the authentic sample and anthracene. Mp = 106-108°C (Lit[60] 105-107°C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.39 (s, 9 H), 6.98 (d, 2 H, J = 8.2 Hz), 7.22-7.68 (m, *12* H); MS (EI): *m/z* (relative intensity) 318 (M^+, 100), 261 (80), 241 (21), 185 (10).

4-(Diphenylphosphino)anisole (49).[61] *Method A:* 4-methoxyphenyltrifluoromethanesulfonate **(33)** (128 mg, 0.5 mmol), palladium(II) acetate (11.2 mg, 0.05 mmol), triphenylphosphine (301 mg, 1.15 mmol) and dry DMF (2 mL) were used to yield 4-(diphenylphosphino)anisole **(49)** (29 mg, 20%) as a white solid. Mp = 101-104°C (Lit[61] 101-103°C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.69 (s, 3 H), 7.10 (dd, 2 H, J = 4.0, 8.1 Hz), 7.24-7.59 (m, 12 H); MS (EI): *m/z* (relative intensity) 292 (M^+, 100), 277 (12), 259 (10), 215 (30), 183 (48). *Method B:* 4-Methoxyphenyltrifluoromethanesulfonate **(33)** (128 mg, 0.5 mmol), palladium(II) acetate (11.2 mg, 0.05 mmol) and triphenylphosphine (301 mg, 1.15 mmol) were used to yield 4-(diphenylphosphino)anisole **(49)** (25% GC yield) was determined by GC with respected to the calibration curve of the authentic sample and anthracene. *Method C:* 4-Bromoanisole (94 mg, 0.5 mmol), palladium(II) acetate (11.2 mg, 0.05 mmol) and triphenylphosphine (301 mg, 1.15 mmol) were used to yield 4-

(diphenylphosphino)anisole **(49)** (49 mg, 33%) as a white solid. *Method D:* 4-Methoxyphenyltrifluoromethanesulfonate **(33)** (128 mg, 0.5 mmol), palladium(II) acetate (11.2 mg, 0.05 mmol) and triphenylphosphine (301 mg, 1.15 mmol) were used to yield 4-(diphenylphosphino)anisole **(49)** (38 mg, 26%) as a white solid.

2-(Diphenylphosphino)anisole (50).[61] *Method A:* 2-Methoxyphenyl-trifluoromethane-sulfonate **(35)** (128 mg, 0.5 mmol), palladium(II) acetate (11 mg, 0.05 mmol), triphenylphosphine (301 mg, 1.15 mmol) and dry DMF (2 mL) were used to yield 2-Methoxyphenyltrifluoromethanesulfonate **(50)** (40 mg, 28%) as a white solid. Mp = 95-98°C (Lit[61] 95-98°C);^{1}H NMR (300 MHz, $CDCl_3$) δ 3.48 (s, 3 H), 7.05 (dd, 2 H, J = 4.0, 8.1 Hz), 7.24-7.59 (m, 12 H); MS (EI): *m/z* (relative intensity) 292 (M^+, 100), 277 (18), 259 (12), 215 (30), 183 (48). *Method B:* 2-Methoxyphenyltrifluoromethane-sulfonate **(35)** (128 mg, 0.5 mmol), palladium(II) acetate (11 mg, 0.05 mmol) and triphenylphosphine (301 mg, 1.15 mmol) were used to yield 2-Methoxyphenyltrifluoromethanesulfonate **(50)** (39 mg, 27%) as a white solid.

1-(Diphenylphosphino)naphthalene (51).[59] 1-Naphthyltrifluoromethanesulfonate **(36)** (138 mg, 0.5 mmol), palladium(II) acetate (11.2 mg, 0.05 mmol), triphenylphosphine (301 mg, 1.15 mmol), anthracene (internal standard) (89 mg, 0.5 mmol) and DMF (2 mL) were used to yield the 1-(diphenylphosphino)naphthalene **(51)** (27% GC yield) was determined by GC with respected to the calibration curve of the authentic sample and anthracene. Mp = 111-115°C (Lit[59] 111-113°C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.89-6.94 (m, 7 H) (7.12-7.46 (m, 10 H) MS (EI): *m/z* (relative intensity) 312 (M^+, 100), 235 (21).

2-(Diphenylphosphino)naphthalene (52).[59] 2-Naphthyltrifluoromethanesulfonate **(37)** (138 mg, 0.5 mmol), palladium(II) acetate (11.2 mg, 0.05 mmol), triphenylphosphine (301 mg, 1.15 mmol), anthracene (internal standard) (89 mg, 0.5 mmol), and DMF (2 mL) were used to yield the 2-(diphenylphosphino)naphthalene **(52)** (51% GC yield) was determined by GC with respected to the calibration curve of the authentic sample and anthracene. ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.87-6.94 (m, 7 H), 7.10-7.19 (m, 12 H). MS (EI): *m/z* (relative intensity) 312 (M^+, 100), 235 (21).

3-(Diphenylphosphino)pyridine (53).[35] 3-Pyridyl trifluoromethanesulfonate **(38)** (1.14 g, 5.0 mmol), palladium(II) acetate (112 mg, 0.5 mmol), triphenylphosphine (3.01 g, 11.5 mmol) were dissolved in dry DMF (20 mL) in a Telfon screw-capped flask under nitrogen. The reaction was heated to 110-115°C for 24 hours and the color of the solution was changed from pale yellow to deep red. The reaction mixture was cooled down and filtered over a short silica gel pad and the pad was washed by dichloromethane. The aqueous extraction was performed by using hydrochloric acid (3 M, 150 mL x 5) and the aqueous phase was collected and neutralized by sodium carbonate solution to pH 7-8. The aqueous solution was extracted by dichloromethane (50 mL x 3). The combined organic phase was washed with brine and dried over $MgSO_4$. The 3-(diphenylphosphino)pyridine **(53)** (263 mg, 20%) was obtained as the pale yellow solid. R_f = 0.8 (hexane/ethyl acetate = 5 : 1); Mp = 98-100°C (Lit[35] 98-100°C);^{1}H NMR (300 MHz, $CDCl_3$) δ 8.34 (d, 1 H, J = 1.4 Hz), 8.30 (d, 1 H, J = 8.3 Hz), 7.92 (t, 1 H, J = 8.2 Hz), 7.27-7.69 (m, 11 H); MS (EI): *m/z* (relative intensity) 263 (M^+, 100), 186 (20).

8-(Diphenylphosphino)quinoline (54).[35] 8-Quinolyltrifluoromethanesulfonate **(39)** (554 mg, 2.0 mmol), palladium(II) acetate (45 mg, 0.2 mmol), triphenylphosphine (1.21 g, 4.6 mmol) were dissolved in dry DMF (8 mL) in a Telfon screw-capped flask under nitrogen. The reaction was heated to 110-115°C for 72 hours and the color of the solution was changed from yellow to red. The reaction mixture was cooled down and concentrated by reduced pressure. The residue was purified by column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 5 : 1) as eluent to afford 8-(diphenylphosphino)quinoline **(54)** (282 mg, 45%) as the pale yellow solid. R_f = 0.5 (hexane/ethyl acetate = 5 : 1); Mp = 134-136°C (Lit[35] 133-136°C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.10-7.14 (m, 1 H), 7.26-7.43 (m, 12 H), 7.78 (d, 1 H, J = 8.0 Hz), 8.12 (d, 1 H, J = 8.2 Hz), 8.85 (dd, 1 H, J = 1.6, 4.2 Hz), ^{31}P NMR (162 MHz, $CDCl_3$) δ -15.11; MS (EI): *m/z* (relative intensity) 313 (M^+, 100), 235 (60), 204 (51), 183 (32), 159 (30).

4-(Bis(3,5-dimethylphenyl)phosphino)acetophenone (59).[33] 4-acetylphenyltriflate **(23)** (134 mg, 0.5 mmol), palladium(II) acetate (11.2 mg, 0.05 mmol), trixylylphosphine **(55)** (398 mg, 1.15 mmol) and DMF (2 mL) were used to yield 4-(bis(3,5-dimethyl)phosphino)acetophenone **(59)** (51 mg, 28%) as pale yellow solid after purified by flash column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 10 : 1) as the eluent. R_f = 0.6 (hexane/ethyl acetate = 10 : 1); m.p. 56-58 °C (Lit[33] 56-58°C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.27 (s, 12 H), 2.59 (s, 3 H), 6.93 (s, 2 H), 6.96 (s, 2 H), 7.00 (s, 2 H), 7.34 (dd, 2 H, J = 1.4, 8.3 Hz), 7.87 (dd, 2 H, J = 1.4, 8.3 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 21.3, 26.6, 127.9 (d, J_{CP} = 6.2 Hz), 131.0, 131.7 (d, J_{CP} = 20.2 Hz), 133.2 (d, J_{CP} = 18.2 Hz), 135.7 (d, J_{CP} = 9.5 Hz), 136.5, 138.1 (d, J_{CP} =7.9 Hz), 145.1 (d, J_{CP} = 14.8 Hz), 198.0; ^{31}P NMR (162

MHz, $CDCl_3$) δ -12.88; MS (EI): *m/z* (relative intensity) 360 (M^+, 100), 345 (8), 317 (12), 253 (8), 241 (15), 225 (13), 211 (22), 193 (16); HRMS (ESIMS) calcd for $C_{24}H_{25}OPH^+$ 361.1716, found 361.1709.

4-(Di(4-methoxyphenyl)phosphino)acetophenone (60).[33] 4-acetylphenyltriflate **(23)** (134 mg, 0.5 mmol), palladium(II) acetate (11.2 mg, 0.05 mmol), tris(4-methoxyphenyl)phosphine **(56)** (405 mg, 1.15 mmol) and DMF (2 mL) were used to yield 4-(di(4-methoxyphenyl)phosphino)acetophenone **(60)** (44 mg, 24%) as pale yellow solid after purified by flash column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 10 : 1) as the eluent. R_f = 0.2 (hexane/ethyl acetate = 10 : 1); m.p. 54-56 °C (Lit[33] 54-56°C); ^1H NMR (300 MHz, $CDCl_3$) δ 2.57 (s, 3 H), 3.81 (s, 6 H), 6.90 (dd, 4 H, J = 2.1, 6.0 Hz), 7.25-7.32 (m, 6 H), 7.85 (dd, 2 H, J = 1.5, 8.4 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 26.6, 55.2, 114.3 (d, J_{CP} = 8.3 Hz), 127.1 (d, J_{CP} = 7.4 Hz), 127.8 (d, J_{CP} = 5.8 Hz), 132.6 (d, J_{CP} = 17.7 Hz), 135.5 (d, J_{CP} = 21.5 Hz), 136.3, 146.1 (d, J_{CP} = 13.9 Hz), 160.5, 197.8; ^{31}P NMR (162 MHz, $CDCl_3$) δ -13.03; MS (EI): *m/z* (relative intensity) 364 (M^+, 100), 349 (10), 281 (9), 257 (10), 245 (30), 229 (8), 214 (40), 199 (18); HRMS (ESIMS) calcd for $C_{22}H_{21}O_3PH^+$ 365.1301, found 365.1289.

4-(Di(4-tolyl)phosphino)acetophenone (61).[33] 4-Acetylphenyltrifluoromethane-sulfonate **(23)** (134 mg, 0.5 mmol), palladium(II) acetate (11.2 mg, 0.05 mmol), tri(4-tolyl)phosphine **(57)** (350 mg, 1.15 mmol) and dry DMF (2 mL) were used to obtain 4-(di(4-tolyl)phosphino)acetophenone **(61)** (49 mg, 30%) as light yellow solid after purified by flash column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 10 : 1) as the eluent. R_f = 0.4 (hexane/ethyl acetate = 10 : 1);

58-60 °C (Lit[33] 58-60°C); ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.35 (s, 6 H), 2.57 (s, 3 H), 7.15-7.25 (m, 8 H), 7.36 (dd, 2 H, J = 1.5, 8.4 Hz), 7.86 (dd, 2 H, J = 1.5, 8.4 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 21.3, 26.6, 127.9 (d, J_{CP} = 6.0 Hz), 129.5 (d, J_{CP} = 7.5 Hz), 132.7 (d, J_{CP} = 9.0 Hz), 133.0 (d, J_{CP} = 18.2 Hz), 134.0 (d, J_{CP} = 20.3 Hz), 136.5, 139.2, 145.3 (d, J_{CP} = 14.3 Hz), 197.8; ^{31}P NMR (162 MHz, $CDCl_3$) δ -12.60; MS (EI): *m/z* (relative intensity) 332 (M^+, 100), 317 (5), 289 (10), 281 (7), 241 (8), 211 (30), 197 (28); HRMS (ESIMS) calcd for $C_{22}H_{21}OPH^+$ 333.1403, found 333.1385.

General Procedure for Palladium Catalyzed Arsination *(Methods A)* and Solvent-free Palladium Catalyzed Arsination *(Methods B)*

4-(Diphenylarsino)acetophenone (70). *Method A:* 4-Acetylphenyltrifluoromethane-sulfonate **(23)** (268 mg, 1.0 mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) and DMF (4 ml) were used to yield 4-(diphenylarsino)acetophenone **(70)** (178 mg, 51%) as a pale yellow solid after purified by column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 10:1) as the eluent. R_f = 0.45 (hexane/ethyl acetate = 10:1); Mp. = 120.3-121°C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.57 (s, 3 H), 7.30-7.35 (m, 10 H), 7.40 (dd, 2 H, J = 1.8, 8.1 Hz), 7.87 (dd, 2 H, J = 1.8, 8.4 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 26.6, 128.1, 128.8, 133.7, 136.8, 138.7, 146.8, 198.0; IR (neat) 1718 cm^{-1}; MS (EI): *m/z* (relative intensity) 348 (M^+, 21), 227 (23), 194 (28), 152 (100); HRMS (ESIMS) Calcd for $C_{20}H_{17}AsO$, 348.0495; Found 348.0504. *Method B:* 4-Acetylphenyltrifluoromethanesulfonate **(23)** (268 mg, 1.0 mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) were used to yield 4-(diphenylarsino)acetophenone **(70)** (164 mg, 47%) as a pale yellow solid.

Methyl 4-(diphenylarsino)benzoate (71). *Method A:* Methyl 4-trifluoromethanesulfonyl-oxybenzoate **(26)** (284 mg, 1.0 mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) and DMF (4 ml) were used to yield methyl 4-(diphenylarsino)benzoate **(71)** (174 mg, 48%) as a white solid after purified by column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 10:1) as the eluent. R_f= 0.56 (hexane/ethyl acetate = 10:1); Mp. = 109-110.5°C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.91 (s, 3 H), 7.32-7.37 (m, 10 H), 7.41 (dd, 2 H, J = 1.4, 8.3 Hz), 7.98 (dd, 2 H, J = 1.7, 6.5 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 52.1, 128.7, 128.8, 129.4, 130.0, 133.5, 133.7, 138.8, 146.4, 167; IR (neat) 1733 cm^{-1}; MS (EI): *m/z* (relative intensity) 364 (M^+, 17), 227 (27), 210 (36), 181 (100), 152 (52); HRMS (ESIMS) Calcd for $C_{20}H_{17}AsO_2$, 364.0445; Found 364.0443. *Method B:* Methyl 4-nonafluorobutanesulfonyloxybenzoate **(71)** (217 mg, 0.5 mmol), $AsPh_3$ (352 mg, 1.15 mmol), $Pd(OAc)_2$ (11 mg, 0.05 mmol) and DMF (2 ml) were used to yield methyl 4-(diphenylarsino)benzoate **(71)** (89 mg, 49%) as a white solid. *Method C:* Methyl 4-trifluoromethanesulfonyloxybenzoate **(26)** (284 mg, 1.0 mmol), palladium(II) acetate (22 mg, 0.1 mmol) and triphenylarsine (704 mg, 2.3 mmol) were put into a Teflon screw-capped flask under nitrogen. The reaction mixture was heated to 115-120°C for 5 days. The reaction was cooled down and dissolved in minimal amount of dichloromethane, which was purified by column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 5/1) as the eluent to obtain the methyl 4-(diphenylarsino)benzoate **(71)** (186 mg, 51%) as white solid after purified by column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 10:1) as the eluent. *Method D:*

Bis(methyl 4-benzoate)phenylarisne (72). Methyl 4-trifluoromethanesulfonyloxy-benzoate **(26)** (284 mg, 1.0 mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) and DMF (4 ml) were heated to 140 °C for 2 days to yield bis(methyl 4-benzoate)phenylarisne **(72)** (56 mg, 13%) and methyl 4-(diphenylarsino)benzoate **(71)** (30%) (spectral data were reported previously) as a white solid after purified by column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 5:1) as the eluent. R_f = 0.29 (hexane/ethyl acetate = 5:1); Mp = 121-122.5°C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 3,91 (s, 6 H), 7.30-7.38 (m, 7 H), 7.40 (d, 2 H, J = 1.8 Hz), 7.98 (dt, 4 H, J = 1.4, 8.4 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 52.2, 129.0, 129.1, 129.5, 130.3, 133.6, 133.8, 138.1, 145.5, 166.9; IR (neat) 1735 cm^{-1}; MS (EI): *m/z* (relative intensity) 422 (M^+, 14), 239 (41), 181 (100), 152 (36); HRMS (ESIMS) Calcd for $C_{22}H_{19}AsO_4$ H^+, 423.0578; Found 423.0586.

4-(Diphenylarsino)nitrobenzene (76). *Method A:* 4-Nitrophenyltrifluoromethane-sulfonate **(21)** (271 mg, 1.0 mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) and DMF (4 ml) were used to yield 4-(diphenylarsino)nitrobenzene **(76)** (144 mg, 41%) as a white solid after purified by column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 10:1) as the eluent. R_f = 0.72 (hexane/ethyl acetate = 10:1); Mp. = 113-114.5°C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.31-7.40 (m, 10 H), 7.48 (dt, 2 H, J = 2.1, 8.7 Hz), 8.14 (dt, 2 H, J = 2.0, 8.8 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 123.1, 129.0, 129.1, 133.7, 134.3, 138.1, 148.0, 149.8; IR (neat) 1349, 1521 cm^{-1}; MS (EI): *m/z* (relative intensity) 351 (M^+, 30), 227 (47), 183 (34), 154 (100); HRMS (ESIMS) Calcd for $C_{18}H_{14}AsNO_2$, 351.0241; Found 351.0227. Elemental Analysis: Calcd for %C 61.55, %H 4.02, %N 3.99; Found %C 61.89, %H 3.90, %N 4.02. *Method B:* 4-Nitrophenyl trifluoromethanesulfonate **(21)** (271 mg, 1.0

mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) were used to yield 4-(diphenylarsino)nitrobenzene **(76)** (140 mg, 40%) as a white solid.

4-(Diphenylarsino)benzonitrile (77). *Method A:* 4-Cyanophenyltrifluoromethanesulfonate **(22)** (251 mg, 1.0 mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) and DMF (4 ml) were used to yield 4-(diphenylarsino)benzonitrile **(77)** (176 mg, 53%) as a white solid after purified by column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 5:1) as the eluent. R_f = 0.60 (hexane/ethyl acetate = 5:1); Mp. = 116.5-118°C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.29-7.37 (m, 10 H), 7.40 (dd, 2 H, J = 1.8, 8.1 Hz), 7.56 (dd, 2 H, J = 1.7, 8.4 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 112.0, 118.8, 129.0, 131.8, 133.7, 134.1, 138.2, 147.2; IR (neat) 2228 cm^{-1}; MS (EI): *m/z* (relative intensity) 331 (M^+, 20), 252 (12), 227 (17), 177 (21), 152 (100); HRMS (ESIMS) Calcd for $C_{19}H_{14}AsN$, 331.0342; Found 331.0340. Elemental Analysis: Calcd for %C 68.89, %H 4.26, %N 4.23; Found %C 68.78, %H 4.39, %N 3.99. *Method B:* 4-Cyanophenyl trifluoromethanesulfonate **(22)** (251 mg, 1.0 mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) were used to yield 4-(diphenylarsino)benzonitrile **(77)** (169 mg, 51%) as a white solid after

4-(Diphenylarsino)benzaldehyde (78). *Method A:* 4-Trifluoromethanesulfonyloxybenzaldehyde **(25)** (254 mg, 1.0 mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) and DMF (4 ml) were used to yield 4-(diphenylarsino)benzaldehyde **(78)** (160 mg, 48%) as a pale yellow solid after purified by column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 8:1) as the eluent. R_f= 0.21 (hexane/ethyl acetate = 10:1); Mp. = 112.5-113.5°C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.30-7.36 (m, 10 H), 7.47 (d, 2 H, J = 8.1 Hz), 7.79 (d, 2 H, J = 7.5 Hz), 9.98 (s, 1 H);

^{13}C NMR (75 MHz, $CDCl_3$) δ 129.5, 130.0, 134.4, 134.7, 136.7, 139.2, 149.5, 192.8; IR (neat) 1700 cm^{-1}; MS (EI): *m/z* (relative intensity) 334 (M^+, 21), 227 (32), 181 (31), 152 (100); HRMS (ESIMS) Calcd for $C_{19}H_{15}AsO$, 334.0339; Found 334.0345. *Method B:* 4-trifluoromethanesulfonyloxybenzaldehyde **(25)** (254 mg, 1.0 mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) were used to yield 4-(diphenylarsino)benzaldehyde **(78)** (170 mg, 50%) as a pale yellow solid.

4-(Diphenylarsino)anisole (79). *Method A:* 4-Methoxyphenyltrifluoromethanesulfonate **(33)** (256 mg, 1.0 mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) and DMF (4 ml) were used to yield 4-(diphenylarsino)anisole **(79)** (145 mg, 43%) as a white solid after purified by column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 20:1) as the eluent. R_f = 0.58 (hexane/ethyl acetate = 20:1); Mp. = 120.0-121.5°C; ^1H NMR (300 MHz, $CDCl_3$) δ 3,74 (s, 3 H), 6.77 (d, 1 H, J =1.8 Hz), 6.86 (dd, 2 H, J = 1.8, 8.1 Hz), 7.27-7.35 (m, 11 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 55.7, 110.2, 121.3, 128.2, 128.5, 130.2, 133.8, 139.2, 161.2; MS (EI): *m/z* (relative intensity) 336 (M^+, 26), 227 (26), 184 (43), 152 (100), 91 (83); HRMS (ESIMS) Calcd for $C_{19}H_{17}AsO$, 336.0495; Found 336.0502. *Method B:* 4-Methoxyphenyltrifluoromethanesulfonate **(33)** (256 mg, 1.0 mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) were used to yield 4-(diphenylarsino)anisole **(79)** (168 mg, 50%) as a white solid.

3-(Diphenylarsino)benzaldehyde (80). *Method A:* 3-Trifluoromethanesulfonyloxybenzaldhyde **(73)** (254 mg, 1.0 mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) and DMF (4 ml) were used to yield 3-(diphenylarsino)benzaldehyde **(80)** (152 mg, 46%) as a white solid after purified by

column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 10:1) as the eluent. R_f= 0.72 (hexane/ethyl acetate = 10:1); Mp. = 108.5-110°C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.33-7.38 (m, 10 H), 7.50 (dd, 1 H, *J* = 1.7, 7.7 Hz), 7.59(dt, 1 H, *J* = 1.4, 7.5 Hz), 7.86 (dt, 2 H, *J* = 1.5, 6.4 Hz) 9.95 (s, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 128.8, 128.9, 129.2, ,129.3, 133.6, 135.3, 136.4, 138.7, 139.5, 141.4, 192.2; IR (neat) 1699 cm^{-1}; MS (EI): *m/z* (relative intensity) 334 (M^+, 28), 227 (38), 180 (42), 152 (100); HRMS (ESIMS) Calcd for $C_{19}H_{15}AsO$, 334.0339; Found 334.0346. *Method B:* 3-Trifluoromethanesulfonyloxybenzaldhyde **(73)** (254 mg, 1.0 mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) were used to yield 3-(diphenylarsino)benzaldehyde **(80)** (160 mg, 48%) as a white solid

3-(Diphenylarsino)anisole (81). *Method A:* 3-Methoxyphenyltrifluoromethane-sulfonate **(34)** (256 mg, 1.0 mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) and DMF (4 ml) were used to yield 3-(diphenylarsino)anisole **(81)** (154 mg, 46%) as a white solid after purified by column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 15:1) as the eluent. R_f= 0.71 (hexane/ethyl acetate = 15:1); Mp. = 119.5-120.5°C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 3,75 (s, 3 H), 6.78 (dd, 2 H, *J* = 1.7, 7.4 Hz), 6.88 (dd, 2 H, *J* = 8.7, 16.1 Hz, 7.28-7.37 (m, 11 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 55.6, 110.2, 121.3, 128.1, 128.2, 128.5, 130.2, 133.8, 133.9, 139.2, 161.1; MS (EI): *m/z* (relative intensity) 336 (M^+, 36), 257 (11), 227 (20), 182 (49), 152 (100); HRMS (ESIMS) Calcd for $C_{19}H_{17}AsO$, 336.0495; Found 336.0491. *Method B:* 2-Methoxyphenyltrifluoromethanesulfonate **(34)** (256 mg, 1.0 mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) were used to yield 4-(diphenylarsino)anisole **(81)** (151 mg, 45%) as a white solid.

2-(Diphenylarsino)benzonitrile (82). *Method A :* 2-Cyanophenyltrifluoromethanesulfonate **(74)** (251 mg, 1.0 mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) and DMF (4 ml) were used to yield 2-(diphenylarsino)benzonitrile **(82)** (103 mg, 31%) as a white solid after purified by column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 5:1) as the eluent. R_f = 0.50 (hexane/ethyl acetate = 5:1); Mp. = 111.5-112.5°C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.13 (dd, 1 H, J = 1.7, 6.5 Hz), 7.30-7.39 (m, 10 H), 7.42 (dt, 2 H, J = 1.8, 6.8 Hz), 7.69 (dd, 1 H, J = 1.7, 6.7 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 117.9, 118.2, 128.8, 129.0, 132.6, 133.5, 133.8, 133.9, 137.6, 144.9; IR (neat) 2230 cm^{-1}; MS (EI): *m/z* (relative intensity) 331 (M^+, 20), 252 (12), 227 (17), 177 (21), 152 (100); HRMS (ESIMS) Calcd for $C_{19}H_{14}AsNH^+$, 332.0420; Found 332.0403. *Method B:* 2-Cyanophenyl trifluoromethanesulfonate **(74)** (251 mg, 1.0 mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) were used to yield 2-(diphenylarsino)benzonitrile **(82)** (103 mg, 31%) as a white solid

2-(Diphenylarsino)anisole (83). *Method A:* 2-Methoxyphenyltrifluoromethanesulfonate **(35)** (256 mg, 1.0 mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) and DMF (4 ml) were used to yield 4-(diphenylarsino)anisole **(83)** (142 mg, 42%) as a white solid after purified by column chromatography on silica gel using a solvent mixture (hexane/ethyl acetate = 40:1) as the eluent. R_f = 0.33 (hexane/ethyl acetate = 20:1); Mp. = 110.5-112°C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 3,71 (s, 3 H), 6.84-6.85 (m, 2 H), 6.91 (d, 1 H, J = 7.2 Hz), 7.22-7.28 (m, 1 H), 7.30-7.35 (m, 10 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 55.1, 114.0, 119.0, 126.0, 128.5, 128.6, 129.5, 133.7, 139.5, 141.0, 159.5; MS (EI): *m/z* (relative intensity) 336 (M^+, 36), 257 (11), 227 (20), 182 (49), 152 (100); HRMS (ESIMS) Calcd for $C_{19}H_{17}AsO$, 336.0495; Found

336.0493. *Method B:* 2-Methoxyphenyltrifluoromethanesulfonate **(35)** (256 mg, 1.0 mmol), $AsPh_3$ (706 mg, 2.3 mmol), $Pd(OAc)_2$ (22 mg, 0.1 mmol) were used to yield 4-(diphenylarsino)anisole **(83)** (164 mg, 49%) as a white solid.

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