3-Indolylphosphines as ligand for palladium in Suzuki–Miyaura coupling reaction of chloroarenes: substituent effects

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ABSTRACT

The ligand 1,3-bis(diphenylphosphino)-1H-indole, **L1** with palladium promotes Suzuki–Miyaura coupling reaction of chloroarenes and benzyl chlorides with arylboronic acids. Structural modification of **L1** established that the phosphine group at C-3 position of indole was crucial to catalysis and its efficacy depended on the nature of the N-substituent. ^{31}P chemical shift values of the substituted indolylphosphines appear to show a correlation with observed trend in catalytic efficiency.

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1. Introduction

Ligand environment around palladium has a strong bearing on the efficacy of palladium catalyzed coupling reactions.[1] Design of new ligands has been a constant pursuit for several research groups primarily to enable abundantly available and inexpensive, yet highly reluctant, chloroarenes to participate in coupling reactions. However, very few definite correlations between ligand structure and reactivity exist to aid such a design, except that alkylphosphines are superior to arylphosphines in general,[2] and NHCs as ligand permit reactions under mild conditions.[3] Over the years, examples of different types of triarylphosphines have appeared in literature, which are also effective with chloroarenes in coupling reactions.[4] Recently, we reported the synthesis and application of bidentate ligands **A** and **B** on an indole scaffold featuring N-PPh$_2$ and C$_7$-PPh$_2$ donor groups (Chart 1).[5] Ligand **A** promoted Suzuki–Miyaura coupling reaction between arylboronic acid and

chloroarenes.[5a] The present work illustrates the utility of indole-based phosphine ligands in coupling reaction of chloroarenes. It also demonstrates that the indole moiety allows for selective modulation of stereoelectronic attributes of the C-3 phosphine by altering the N-substituents.

During synthesis of ligand **A**, a byproduct was isolated, which was later identified as a regioisomer of the ligand **A**. This new diphosphine, **L1** (Chart 2), was also found to be useful as a ligand for palladium in Suzuki–Miyaura coupling reaction. In this report we describe: (a) practical synthesis for the ligand **L1** and its variants, (b) comparative study of Pd-catalyzed coupling reaction of arylboronic acid with chloroarenes using them, (c) crystal structure determination of a bimetallic complex of palladium and the ligand **L1**, and, (d) ^{31}P NMR study of these phosphines to derive a working
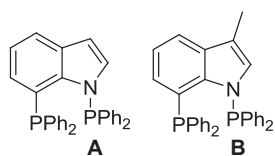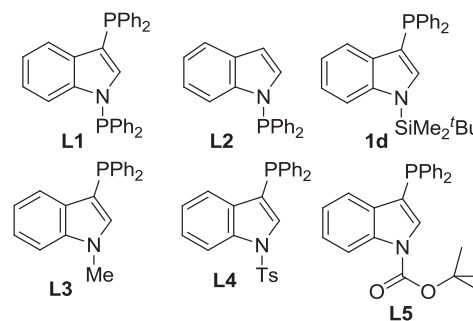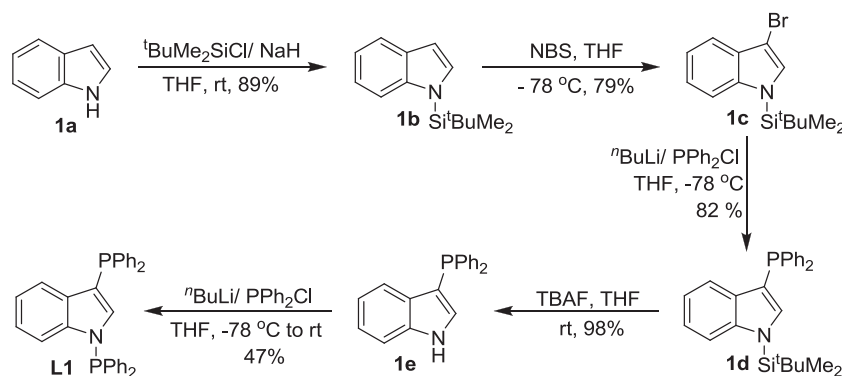

Chart 1.

Chart 2.

correlation between the performance of a ligand and chemical shift of phosphorus nucleus.

2. Results and discussions

A concise synthesis of **L1** was accomplished in five steps in an overall yield of 27% starting from commercially available indole (Scheme 1). Protection of nitrogen of the indole with TBDMS chloride followed by treatment with NBS afforded the 3-bromo-indole derivative, **1c**.[6] Bromine–lithium exchange at low temperature followed by quench with ClPPh$_2$ in THF furnished the desired phos-

solvent, N,N-dimethylacetamide (DMA) was evidently the best choice (entry 6, Table 1), although DMF was a close second (entry 5, Table 1). Yield dropped if the temperature was lowered (entry 7, Table 1). The lower boiling solvents were clearly not suitable (entries 1–4, Table 1).

Once the solvent and temperature were selected, several bases were screened for optimum yield. The results are summarized in Table 2. It was found that Pd(CH$_3$CN)$_2$Cl$_2$ as catalyst precursor and NaOH as base afforded the highest yield of product (entry 7, Table 2). Use of an additional equivalent of ligand did not depress the yield (entry 8, Table 2). The second best choice was Pd$_2$dba$_3$ with met-

Scheme 1. Synthesis of ligand **L1**.

phine **1d** in excellent yield. While removal of the silyl protective group proceeded with nearly quantitative yield (98%), introduction of −PPh$_2$ group on the nitrogen of 3-diphenylphosphino-indole proved less rewarding (47%). The product was purified by column chromatography followed by crystallization and isolated as a white, crystalline solid (**L1**). Both spectral characteristics and analytical data for this compound were consistent with the assigned structure. The structure was later confirmed by X-ray crystallography (see Supplementary data).

A preliminary investigation revealed that the reaction between 4-chloroacetophenone and phenylboronic acid in presence of ligand **L1** and bis(acetonitrile)-dichloropalladium (4 mol %, Pd:**L1** 1:1) in THF at 65 °C for 8 h afforded the coupled product in 14% yield. Subsequent modification of the reaction conditions resulted in a considerable improvement in yield. Table 1 summarizes the results of screening of solvents for the coupling reaction. The

Table 1
Suzuki–Miyaura coupling reaction—screening of solvents[a]
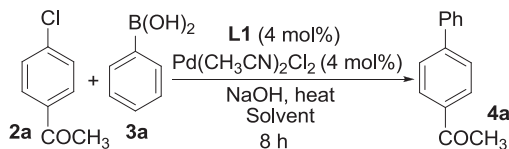
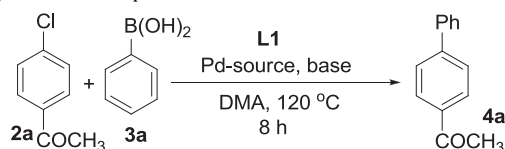| Entry	Solvent	T (°C)	Yield (%)[b]
1	THF	65	14
2	CH$_3$CN	80	18
3	Dioxane	100	38
4	Toluene	110	22
5	DMF	120	82
6	DMA	120	88
7	DMA	90	73
8	DMSO	125	41

[a] Reaction condition: 4-chloroacetophenone (0.75 mmol), phenylboronic acid (1.125 mmol), Pd (CH$_3$CN)$_2$Cl$_2$ (4 mol %), **L1** (4 mol %), NaOH (1.5 mmol), solvent (1 mL), argon atmosphere.
[b] Isolated yield of the product.

Table 2
Screening of base and Pd-precursor[a]

Entry	Pd (mol %)	**L1** (mol %)	Base	Yield (%)[b]
1	Pd(CH$_3$CN)$_2$Cl$_2$ (4)	4	K$_3$PO$_4$	57
2	Pd(CH$_3$CN)$_2$Cl$_2$ (4)	4	K$_2$CO$_3$	26
3	Pd(CH$_3$CN)$_2$Cl$_2$ (4)	4	CsF	68
4	Pd(CH$_3$CN)$_2$Cl$_2$ (4)	4	Cs$_2$CO$_3$	78
5	Pd(CH$_3$CN)$_2$Cl$_2$ (2)	2	NaOH	56
6	Pd(CH$_3$CN)$_2$Cl$_2$ (3)	3	NaOH	60
7	Pd(CH$_3$CN)$_2$Cl$_2$ (4)	4	NaOH	88
8	Pd(CH$_3$CN)$_2$Cl$_2$ (4)	8	NaOH	87
9	Pd(OAc)$_2$ (4)	4	NaOH	79
10	PdCl$_2$ (4)	4	NaOH	73
11	Pd$_2$(dba)$_3$ (4)	4	NaOH	80

[a] Reaction condition: 4-chloroacetophenone (0.75 mmol), phenylboronic acid (1.125 mmol), base (1.5 mmol), solvent (1 mL), argon atmosphere.
[b] Isolated yield of the product.

al:ligand ratio 1:1 (entry 11, Table 2). Yield of product was diminished if less than 4 mol % catalyst was used (entries 5 and 6, Table 2).

Using the optimized condition, a range of chloroarenes and chloroheterocycles were subjected to Suzuki–Miyaura coupling reaction. The results collected in Table 3 reveal that electron-deficient aromatic or heteroaromatic chloro derivatives afforded high yield of coupled products. Those with an electron-releasing substituent afforded the products in moderate to good yield under similar condition. Yield of product for methoxy-substituted chloroarenes was less than those for methyl substituted chloroarene (compare entries 5 and 7, Table 3). A tosylate instead of a chloro substituent was unreactive in this reaction (entry 13, Table 3).

It was gratifying to note that benzyl chlorides underwent coupling reaction with arylboronic acid to afford high yield of desired products under similar condition (Table 4). The importance of

Table 3
Suzuki–Miyaura coupling of aryl, heteroaryl chlorides with arylboronic acids using ligand L1[a]

$R^1Cl + $ **2** (boronic acid **3**) $\xrightarrow[\text{120 °C}]{\substack{\textbf{L1} \text{ (4 mol\%)} \\ Pd(CH_3CN)_2Cl_2 \text{ (4 mol\%)} \\ NaOH, DMA}}$ **4**

$R^2 = H, 4\text{-OMe}, 4\text{-CH}_3$

Entry	R^1Cl	Time (h)	R^1–R^2	Yield (%)[b]
1	MeOC–C6H4–Cl **2a**	8	biphenyl–COMe **4a**	88
2	O2N–C6H4–Cl **2b**	6	biphenyl–NO2 **4b**	72
3	NC–C6H4–Cl **2c**	6	biphenyl–CN **4c**	70
4	**2d** C6H4–Cl	9	MeO–biphenyl **4d**	55
5	MeO–C6H4–Cl **2e**	10	biphenyl–OMe **4d**	58
6	**2f** Cl, MeO	10	H3C–biphenyl–OMe **4e**	56
7	H3C–C6H4–Cl **2g**	10	biphenyl–CH3 **4f**	76
8	**2h** Cl, NO2	6	biphenyl, O2N **4g**	95
9[c]	**2a**	8	naphthyl–C6H4–COMe **4h**	81
10	**2i** Cl-pyridine	5	Ph-pyridine **4i**	75
11	**2j** CN, Cl-pyridine	5	CN, Ph-pyridine **4j**	85
12	**2k** Cl-pyridine	5	Ph-pyridine **4k**	73
13	MeO–C6H4–OTs **2l**	10	biphenyl–OMe **4d**	—[d]

[a] Reaction condition: chloroarene (0.75 mmol), boronic acid (1.125 mmol), Pd(CH$_3$CN)$_2$Cl$_2$ (4 mol %), **L1** (4 mol %), NaOH (1.5 mmol), DMA (1 mL), argon atmosphere.
[b] Isolated yield of the product.
[c] 1-Naphthaleneboronic acid was used.
[d] Product was not detected.

diarylmethanes and the difficulties of synthesizing them using Suzuki–Miyaura coupling reactions have been highlighted in the literature.[7] In the present study, the reaction occurred regiose-lectively at the benzyl position for chloro substituted arenes (entry 4, Table 4) in preference to the chlorine attached to aromatic nucleus.

The disposition of –PPh$_2$ groups on the indole framework in ligand **L1** suggested a priori that a bidentate mode of binding to the same metal centre is not possible for ligand **L1**. It took a substantial effort to grow crystals of the complex prepared according to the reaction depicted in Scheme 2, from dichloromethane/acetonitrile.

Table 4
Suzuki–Miyaura coupling of benzyl chlorides with arylboronic acids using ligand **L1**[a]

Entry	R^1Cl	Time (h)	R^1–R^2	Yield (%)[b]
1	**2m**	7	**4l**	98
2	**2n**	6	**4m**	94
3	**2o**	6	**4n**	89
4[c]	**2p**	7	**4o**	74
5	**2q**	10	**4l**	86

[a] Reaction condition: chloroarene (0.75 mmol), boronic acid (1.125 mmol), Pd(CH$_3$CN)$_2$Cl$_2$ (4 mol %), **L1** (4 mol %), NaOH (1.5 mmol), DMA (1 mL), argon atmosphere.
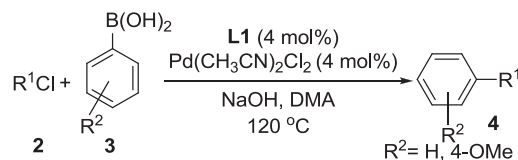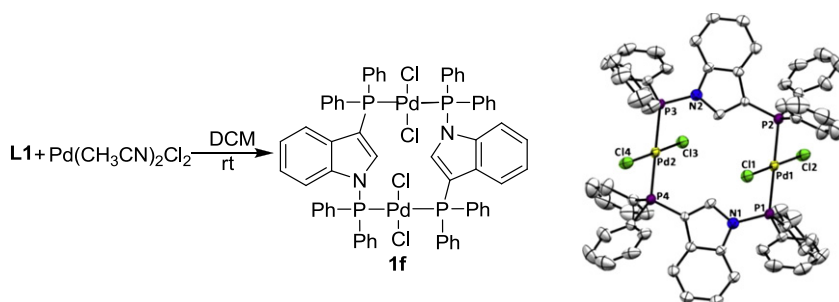[b] Isolated yield of the product.
[c] 1 equiv boronic acid was used.

Scheme 2. Synthesis of palladium complex **1f**.

The crystal structure revealed a bimetallic, cyclic structure **1f** with metal–ligand ratio 1:1. The two chlorine atoms on each palladium were placed *trans* to each other where each phosphine of the ligand **L1** was bound to a different palladium centre. It is important to note that both types of phosphines participate in coordination with palladium.[8] This bimetallic complex was not as efficient as a catalyst compared to the complex generated in situ (as in reactions described above) and furnished only a moderate yield (51%) of product after 8 h from 4-chloroacetophenone. Therefore, it is not possibly the catalyst precursor in this reaction described. Since both phosphino groups were found to coordinate with the metal in the bimetallic complex, we decided to address which of the phosphines—at *C-3* or at N-1—contributes more significantly to the catalytic process.

To assess the relative contribution of the two phosphines as unidentate ligand to palladium, therefore, ligands **L2** and **L3** were synthesized (Scheme 3). The ligand **L2** was prepared in a straightforward manner from indole. Similarly, indole (**1a**) was readily modified with appropriate reaction sequences to yield ligand **L3**. The ligands **L2** and **L3** were all white or off-white, crystalline solid whose structures were consistent with spectroscopic and analytical data.
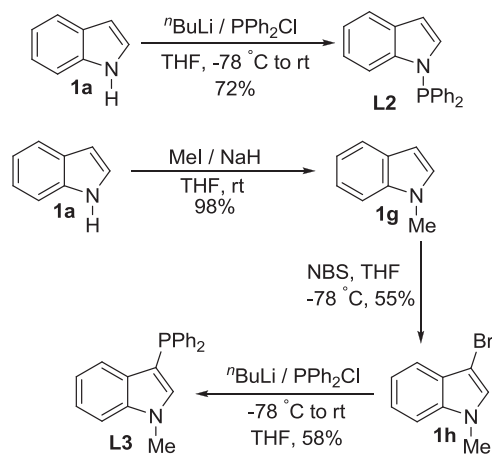
Scheme 3. Synthesis of ligand **L2** and **L3**.

Using Pd–ligand ratio as 1:1 with ligands **L2**, **L3** and **1d** (N–TBDMS instead of N–Me as in **L3**) resulted in extensive deposition of Pd black and a poor reaction. We reasoned that in case of ligand **L1**, we were actually using two phosphines per molecule. This would be significant in case of monodentate complex where extra phosphine could simply stabilize resting Pd (0) intermediates and delay deposition of Pd black.[4f] We, therefore, carried out experiments with a Pd–ligand ratio of 1:2 and the reactions proceeded smoothly. The results are summarized in Table 5. As a first approximation, we used an equimolar mixture of **1d** and **L2** to simulate the effect of using ligand **L1**. The yields of product were comparable (compare entries 1 and 4, Table 5). The yield remained practically unchanged when only ligand **1d** and palladium in a ratio of 1:2 was used (entry 6, Table 5) but yield dropped if **1d**: Pd was 1:1 (entry 5, Table 5). The amount of metal–ligand combination could be reduced to 1 mol % in palladium but a 15 h reaction time was required to obtain a similar yield of product (entry 7, Table 5). That silicon was not playing any role in this reaction was demonstrated by use of ligand **L3** (compare entries 6 and 8, Table 5). Use of ligand **L2** alone afforded a moderate yield of product whether under identical condition (entry 2, Table 5), or with a prolonged reaction time (entry 3, Table 5).

A variety of aromatic and heteroaromatic and benzyl chlorides were used as substrates in Suzuki–Miyaura coupling with arylboronic acids using the ligand **1d** under the conditions described above. The data in Table 6 revealed that yield of cross-coupled products was as good as these depicted in Table 3 and Table 4. These results indicate that the phosphine group on C-3 of the indole scaffold was crucial to the reaction studied,[9] irrespective of the bulk of N-substituents.

Since reactivity of C-3 of the indole is directly affected by N-1substituent, we sought to establish whether the property of phosphines at C-3 was also affected by changes at N-1. The ligands **L4** and **L5** were prepared according to the following procedure (Scheme 4) to examine this possibility.
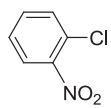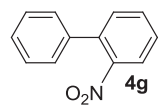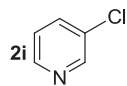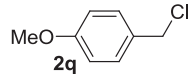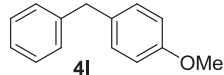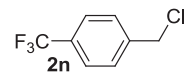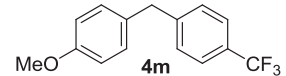
Relative effectiveness of the ligands **L4** and **L5** were assessed with respect to the reaction of 4-chloroacetophenone. The results are summarized in Table 7. When the nitrogen of indole was protected with a *t*-Boc group (**L5**), the yield of the coupling reaction was only 12% (entry 3, Table 7), which dropped to 0% when a tosyl group was placed on N-1 (**L4**) (entries 1 and 2, Table 7). This is a remarkable example of electronic tuning of ligand activity of phosphines.

Table 5
Screening of ligand[a]

Entry	Pd (mol %)	L (mol %)	Time (h)	Yield (%)[b]
1	Pd(CH₃CN)₂Cl₂ (4)	**L1** (4)	8	88
2	Pd(CH₃CN)₂Cl₂ (4)	**L2** (8)	8	58
3	Pd(CH₃CN)₂Cl₂ (4)	**L2** (8)	24	60
4	Pd(CH₃CN)₂Cl₂ (4)	**1d** (4)+**L2** (4)	8	89
5	Pd(CH₃CN)₂Cl₂ (4)	**1d** (4)	8	81
6	Pd(CH₃CN)₂Cl₂ (4)	**1d** (8)	8	91
7	Pd(CH₃CN)₂Cl₂ (1)	**1d** (2)	15	87
8	Pd(CH₃CN)₂Cl₂ (4)	**L3** (8)	8	90

[a] Reaction condition: chloroarene (0.75 mmol), boronic acid (1.125 mmol), Pd(CH₃CN)₂Cl₂ (mol %), ligand (mol %), NaOH (1.5 mmol), DMA (1 mL), argon atmosphere.
[b] Isolated yield of the product.

Table 6
Cross-coupling of aryl and heteroaryl and benzyl chlorides with arylboronic acid using ligand **1d**[a]

Entry	R¹ Cl	Time (h)	R¹–R²	Yield (%)[b]
1	**2a**	8	**4a**	91
2	**2d**	9	**4d**	78
3	**2e**	10	**4d**	72
4	**2e**	10	**4p**	67
5	**2r**	10	**4q**	62
6	**2e**	10	**4r**	69
7	**2g**	10	**4f**	79
8	**2f**	10	**4e**	79

Table 6 (continued)

Entry	R^1 Cl	Time (h)	R^1–R^2	Yield (%)[b]
9	**2h** (phenyl with Cl, NO$_2$)	6	**4g** (biphenyl, O$_2$N)	97
10	**2i** (pyridine with Cl)	5	**4i** (pyridine with Ph)	85
11	**2q** (MeO-phenyl-CH$_2$Cl)	10	**4l** (benzyl-phenyl-OMe)	89
12	**2n** (F$_3$C-phenyl-CH$_2$Cl)	6	**4m** (MeO-benzyl-phenyl-CF$_3$)	92

[a] Reaction condition: chloroarene (0.75 mmol), boronic acid (1.125 mmol), Pd(CH$_3$CN)$_2$Cl$_2$ (4 mol %), **1d** (8 mol %), NaOH(1.5 mmol), DMA (1 mL), argon atmosphere.
[b] Isolated yield of the product.
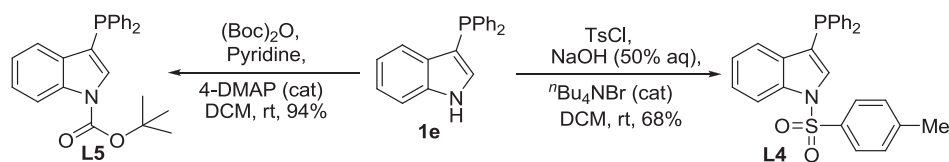
Scheme 4. Synthesis of ligand **L4** and **L5**.

Table 7
Effect of ligand **L4** and **L5**[a]
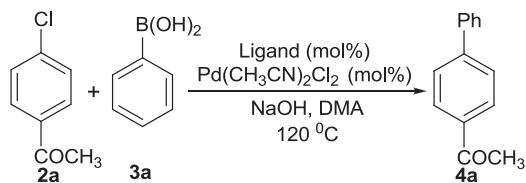
Entry	Pd (mol %)	L (mol %)	Time (h)	Yield (%)[b]
1	Pd(CH$_3$CN)$_2$Cl$_2$ (4)	**L4** (8)	8	—[c]
2	Pd(CH$_3$CN)$_2$Cl$_2$ (4)	**L4** (16)[d]	8	—[c]
3	Pd(CH$_3$CN)$_2$Cl$_2$ (4)	**L5** (8)	8	12

[a] Reaction condition: chloroarene (0.75 mmol), boronic acid (1.125 mmol), Pd(CH$_3$CN)$_2$Cl$_2$ (mol %), ligand (mol %), NaOH (1.5 mmol), DMA (1 mL), argon atmosphere.
[b] Isolated yield of the product.
[c] Product was not detected.
[d] Ligand was added in three portions over a period of time.

Interestingly, the ^{31}P chemical shifts of these phosphines appear to correlate with observed reactivity difference among ligands **L4** and **L5** vis-à-vis **L1** or **1d**. The ^{31}P NMR signals of 3-PPh$_2$ in ligands **L1**, **1d** and **L3** appear at −27.28, −26.48 and −27.76 ppm, respectively. In comparison, the ^{31}P NMR signal of ligands **L4** and **L5** are considerably deshielded and appear at 21.53 and 17.99 ppm. It appears that this deshielding effect on phosphorus parallels the reduction in the ability of phosphorus nucleus in **L4** and **L5** to coordinate with palladium. When an equimolar mixture of ligand and Pd(CH$_3$CN)$_2$Cl$_2$ was analyzed by ^{31}P NMR spectroscopy, it was observed that the ^{31}P NMR signals of ligands **1d** and **L3** were shifted all the way to 41.82 and 43.01 ppm, respectively, indicating a significant amount of 1:1 complex formation. For ligands **L4** and **L5**, the ^{31}P NMR signals remained practically unaffected, suggesting insignificant metal–ligand coordination.[10]

Phosphines, such as ArP(cyclohexyl)$_2$ has ^{31}P signals at −8 to −20 ppm and they often are ligands of choice for Pd-catalyzed reactions with chloroarenes. We believe that indole-3-PPh$_2$ ligands described here also should display shielded ^{31}P NMR signals in the region −12 to −28 ppm to be useful in reactions with chloroarenes (see Ref.4 as well for related data).

3. Conclusion

In summary, we described a new 1,3-diphenylphosphinoindole, **L1** as a useful ligand for palladium catalyzed Suzuki–Miyaura reaction. A closer investigation revealed that the ligand operates in a monodentate mode and the 3-diphenylphosphinoindole derivatives were effective as a class of ligand. The donor property and consequent catalytic efficacy of the phosphino group was found to be dependant on the nature of the N-substituent of the indole. A trend of the chemical shift of the ^{31}P nucleus seems to be in tune with the observed reactivity trait.

4. Experimental section

4.1. General information

Unless otherwise noted all starting materials were obtained from commercial suppliers. Organic solvents were dried and distilled as described elsewhere. All reactions were carried out in an oven-dried flask under argon atmosphere. Column chromatography was performed with silica gel 230–400 mesh. All ^{1}H NMR, ^{13}C NMR and ^{31}P NMR spectra were recorded in CDCl$_3$ solution and reported in ppm (δ). ^{1}H NMR 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. ^{13}C NMR spectra were referenced to CDCl$_3$ (δ 77.0 ppm, the middle peak). ^{31}P NMR spectra were referenced to PPh$_3$ externally. High resolution mass spectra (HRMS) were obtained on a FT-ICR mass spectrometer

(ESIMS—Micromass Q-TOF micro). CHN analysis was performed with CHNS analyzer (2400 series II). X-ray single crystal data were collected using MoKα (λ=0.7107 Å) radiation. Data collection, data reduction, structure solution/refinement were carried out using the software package of BRUKER APEX II. The single crystal structures of the free ligand (**L1**) and Pd—**L1** complex (**1f**) were solved by direct and Patterson method, respectively, and refined in a routine manner.

*4.1.1. 1-(tert-Butyldimethylsilyl)-1H-indole (**1b**).*[6] R_f (10% EtOAc/Petroleum ether) 0.33; IR λ$_{max}$ (KBr, cm^{-1}) 3064.6, 2950.5, 2929.7, 2855.9, 1512.0, 1427.6, 1449.9, 1284.3, 1271.6, 1255.8, 1158.9, 1140.9, 984.2, 840.1; ^{1}H NMR (CDCl$_3$, 300 MHz, ppm) δ 7.61 (d, *J*=6.5 Hz, 1H), 7.49 (d, *J*=8.1 Hz, 1H), 7.15–7.05 (m, 3H), 6.59 (d, *J*=3.2 Hz, 1H), 0.90 (s, 9H), 0.57 (s, 6H); ^{13}C NMR (CDCl$_3$, 75 MHz, ppm) δ 141.1, 131.5, 131.1, 121.5, 120.8, 119.9, 114.0, 104.9, 26.5, 19.7, −3.8; HRMS (ESI) *m/z* calcd for C$_{14}$H$_{22}$NSi [M+H]$^+$ 232.1522, found 232.1517.

*4.1.2. 3-Bromo-1-(tert-butyldimethylsilyl)-1H-indole (**1c**).*[6] R_f (10% DCM/Petroleum ether) 0.49; IR λ$_{max}$ (KBr, cm^{-1}) 2954.0, 2931.0, 2855.5, 1716.1, 1608.8, 1507.8, 1466.1, 1446.0, 1417.2, 1405.1, 1287.0, 1256.3, 1197.0, 1173.6, 1156.1, 1139.2, 1014.0, 942.7, 923.3, 847.0; ^{1}H NMR (CDCl$_3$, 300 MHz, ppm) δ 7.67–7.64 (m, 1H), 7.57–7.55 (m, 1H), 7.30–7.26 (m, 3H), 1.02 (s, 9H), 0.68 (s, 6H); ^{13}C NMR (CDCl$_3$, 75 MHz, ppm) δ 140.4, 130.1, 129.8, 122.6, 120.7, 119.3, 114.2, 93.8, 26.4, 19.5, −3.8; HRMS (ESI) *m/z* calcd for C$_{14}$H$_{20}$BrNSi [M+H]$^+$ 310.0627, found 310.0623.

*4.1.3. 1-(tert-Butyldimethylsilyl)-3-(diphenylphosphino)-1H-indole (**1d**).* To a stirred solution of 3-bromo-1-(*tert*-butyldimethylsilyl) indole (**1c**) (4.83 g, 15.6 mmol) in THF (60 mL) under argon atmosphere, was added *n*-BuLi (9.4 mL, 18.7 mmol, 2 M in THF) dropwise at −78 °C. The mixture was stirred for 2 h at −78 °C and chlorodiphenylphosphine (4.3 mL, 23.4 mmol, 1 M in THF) in THF (10 mL) was added dropwise at this temperature. Stirring was continued for 4 h at −78 °C. It was then slowly warmed to rt, quenched with saturated NH$_4$Cl at 0 °C and extracted with diethyl ether (2×100 mL). The combined organic layer was washed subsequently with water and brine and dried over anhydrous Na$_2$SO$_4$. Evaporation of solvent under reduced pressure gave the crude product. Purification by flash column chromatography (silica gel, 10% dichloromethane/petroleum ether) afforded (**1d**) as a white solid (5.33 g, 82%); R_f (10% DCM/Petroleum ether) 0.53; mp 71 °C–73 °C; IR λ$_{max}$ (KBr, cm^{-1}) 3066.9, 2928.0, 2854.7, 1496.8, 1465.9, 1448.6, 1431.2, 1278.8, 1257.6, 1205.6, 1147.7, 1116.8, 1091.7, 943.2, 841.0, 810.1, 790.8, 748.4, 736.8, 694.4; ^{1}H NMR (CDCl$_3$, 500 MHz, ppm) δ 7.58 (d, *J*=8.5 Hz, 1H), 7.50–7.47 (m, 4H), 7.36–7.33 (m, 7H), 7.29 (d, *J*=3 Hz, 1H), 7.19 (t, *J*=8 Hz, 1H) 7.03 (t, *J*=7.5 Hz, 1H), 0.96 (s, 9H), 0.62 (s, 6H); ^{13}C NMR (CDCl$_3$, 125 MHz, ppm) δ 143.0, 143.0, 139.9, 139.7, 137.1, 133.1, 132.9, 132.8, 128.4, 128.4, 122.1, 121.2, 121.2, 120.4, 114.4, 108.9, 26.4, 26.4, 19.5, −3.9; ^{31}P NMR (CDCl$_3$, 202.44 MHz, ppm) δ −26.48 (s); HRMS (ESI) *m/z* calcd for C$_{26}$H$_{31}$NPSi [M+H]$^+$ 416.1963, found 416.1962.

*4.1.4. 3-(Diphenylphosphino)-1H-indole (**1e**).* To a stirred solution of 1-(*tert*-Butyldimethylsilyl)-3-(diphenylphosphino)-1H-indole (**1d**) (1.17 g, 2.65 mmol) in THF (20 mL) under argon atmosphere, a solution of tetrabutylammonium fluoride in THF (2.9 mL, 2.91 mmol, 1 M) was added dropwise. After stirring for 30 min, the reaction mixture was quenched with water and extracted with diethyl ether (2×30 mL). The combined organic layer was washed with water and brine and dried over anhydrous Na$_2$SO$_4$. Evaporation of solvent under reduced pressure afforded the crude product. Purification by flash column chromatography (silica gel, 20% EtOAc/petroleum ether) provided the desilylated compound (**1e**) as a white solid (831 mg, 98%); R_f (10% EtOAc/Petroleum ether) 0.28;

mp 89 °C–91 °C; IR λ$_{max}$ (KBr, cm^{-1}) 3398.7, 3047.6, 1502.6, 1481.4, 1454.4, 1431.2, 1404.2, 1238.3, 1093.7, 742.6; ^{1}H NMR (CDCl$_3$, 500 MHz, ppm) δ 8.48 (s, 1H), 7.54–7.39 (m, 6H), 7.32–7.31 (m, 6H), 7.22 (t, *J*=7.5 Hz, 1H), 7.10 (t, *J*=2.5 Hz, 1H), 7.05 (t, *J*=7.5 Hz, 1H); ^{13}C NMR (CDCl$_3$, 125 MHz, ppm) δ 137.6, 137.6, 133.2, 133.0, 132.1, 131.9, 129.9, 129.8, 128.5, 128.4, 122.7, 121.2, 121.2, 120.4, 111.6; ^{31}P NMR (CDCl$_3$, 202.44 MHz, ppm) δ −27.49 (s); HRMS (ESI) *m/z* calcd for C$_{20}$H$_{17}$NP [M+H]$^+$ 302.1099, found: 302.1096.

*4.1.5. 1,3-bis(Diphenylphosphino)-1H-indole (**L1**).* To a stirred solution of 3-(diphenylphosphino)-1H-indole (**1e**) (301.3 mg, 1 mmol) in THF (5 mL) under argon atmosphere was added *n*-BuLi (0.6 mL, 1.2 mmol, 2 M in THF) dropwise at −78 °C. The mixture was slowly warmed to rt and then stirred for a further 2 h at rt. After the mixture cooled to −78 °C, chlorodiphenylphosphine (0.2 mL, 1.2 mmol, 1 M in THF) in THF (2 mL) was added dropwise. The mixture was then warmed to rt and stirred for a further 6 h. It was then quenched with saturated NH$_4$Cl solution at 0 °C and extracted with diethyl ether (2×25 mL). The combined organic layer was washed with water and brine and dried over anhydrous Na$_2$SO$_4$. Evaporation of solvent under reduced pressure gave the crude product. Purification by flash column chromatography (silica gel, 2% ethyl acetate/petroleum ether) afforded ligand (**L1**) as white solid (662 mg, 47%); R_f (10% EtOAc/Petroleum ether) 0.47; mp 119 °C–121 °C; IR λ$_{max}$ (KBr, cm^{-1}) 3068.8, 3043.8, 1583.6, 1479.4, 1467.9, 1444.7, 1433.2, 1267.3, 1205.6, 1141.9, 1132.3, 1091.8, 937.4, 738.8, 690.5; ^{1}H NMR (CDCl$_3$, 500 MHz, ppm) δ 7.77 (d, *J*=8 Hz, 1H), 7.42–7.35 (m, 10H), 7.33–7.26 (m, 11H), 7.21 (t, *J*=7.5 Hz, 1H), 7.06 (t, *J*=7.5 Hz, 1H), 6.93 (t, *J*=2.5 Hz, 1H); ^{13}C NMR (CDCl$_3$, 125 MHz, ppm) δ 142.9, 142.9, 142.8, 142.7, 138.3, 138.0, 137.4, 137.3, 135.9, 135.8, 133.1, 133.0, 132.3, 132.1, 130.0, 128.9, 129.0, 128.5, 128.4, 122.8, 121.4, 121.3, 112.8, 112.7, 112.1, 111.6, 104.8; ^{31}P NMR (CDCl$_3$, 202.44 MHz, ppm) δ 37.96 (s), −27.28 (s); HRMS (ESI) *m/z* calcd for C$_{32}$H$_{26}$NP$_2$ [M+H]$^+$ 486.1540, found 486.1535. Details of crystal structure determination are provided in the Supplementary data.

*4.1.6. 1-(Diphenylphosphino)-1H-indole (**L2**).* To a stirred solution of indole (**1a**) (116 mg, 2 mmol) in THF (6 mL) under argon atmosphere, was added *n*-BuLi (1.3 mL, 2.1 mmol, 1.6 M in THF) dropwise at −78 °C. The mixture was slowly warmed to rt and stirred for 1 h at rt. After the mixture cooled to −78 °C, chlorodiphenylphosphine (0.4 mL, 2.1 mmol, 1 M in THF) in THF (2 mL) was added dropwise. The mixture was then warmed to rt and stirred for a further 10 h. It was then quenched with saturated NH$_4$Cl solution at 0 °C and extracted with diethyl ether (2×25 mL). The combined organic layer was washed subsequently with water and brine and dried over anhydrous Na$_2$SO$_4$. Evaporation of solvent under reduced pressure gave the crude product. Purification by flash column chromatography (silica gel, 7% Ethyl acetate/petroleum ether) afforded (**L2**) as white solid (433 mg, 72%). R_f (10% EtOAc/Petroleum ether) 0.75; mp: 67 °C–69 °C; IR λ$_{max}$ (KBr, cm^{-1}): 3065.0, 1601.0, 1538.6, 1477.5, 1444.7, 1429.3, 1290.4, 1267.3, 1201.7, 1151.5, 1132.3, 744.6; ^{1}H NMR (CDCl$_3$, 500 MHz, ppm). δ 7.78 (d, *J*=8.5 Hz, 1H), 7.61 (d, *J*=8 Hz, 1H), 7.38–7.30 (m, 10H), 7.22–7.14 (m, 2H), 6.97 (s, *J*=2 Hz, 1H), 6.63 (s, *J*=2 Hz, 1H); ^{13}C NMR (CDCl$_3$, 125 MHz, ppm): δ 141.4, 141.3, 136.5, 136.4, 132.3, 132.1, 130.6, 130.3, 129.8, 128.9, 128.8, 122.3, 121.0, 120.9, 112.4, 112.3, 106.7; ^{31}P NMR (CDCl$_3$, 202.44 MHz, ppm): δ 36.14 (s); HRMS (ESI) *m/z* calcd for C$_{20}$H$_{17}$NP [M+H]$^+$: 302.1099, found 302.1096.

*4.1.7. 1-Methyl-1H-indole (**1g**).* To a suspended solution of NaH (6.00 g, 60% dispersion in mineral oil, 250 mmol) in THF (50 mL), indole (11.7 g, 100 mmol) dissolved in THF (50 mL) was added dropwise at 0 °C. The heterogeneous mixture was stirred at 0 °C for 15 min and 1 h at rt. The mixture was then cooled to 0 °C, treated

with iodomethane (8.4 mL, 132 mmol), and allowed to warm to rt. After 30 min, the reaction mixture was cooled to 0 °C, quenched with saturated NH_4Cl (200 mL), and extracted with ether (3×50 mL). The organic layers were combined, washed with brine, dried over anhydrous Na_2SO_4 and concentrated in vacuo. The resulting oil was purified by flash column chromatography (silica-gel, 5% Dichloromethane/petroleum ether) to provide 1-methyl-1H-indole (1g) (13.0 g, 98% yield) as colourless oil. R_f (10% DCM/Petroleum ether) 0.40; IR λ_{max} (KBr, cm^{-1}) 3053.6, 2940.9, 1513.0, 1488.4, 1329.7, 1316.4, 1242.0, 739.8; ^{1}H NMR (500 MHz, CDCl$_3$): δ 7.82 (d, J=8.0 Hz, 1H), 7.47 (d, J=8.0 Hz, 1H), 7.40 (t, J=7 Hz, 1H), 7.29 (t, J=7.5 Hz, 1H), 7.16 (d, J=3 Hz, 1H), 6.66 (d, J=3.0 Hz, 1H), 3.87 (s, 3H); ^{13}C NMR (CDCl$_3$, 125 MHz, ppm) δ 136.8, 128.8, 128.6, 121.5, 120.9, 119.3, 109.3, 100.9, 32.8.

4.1.8. *3-Bromo-1-methyl-1H-indole (1h).* To a stirred solution of 1-methyl-1H-indole (1g) (4 g, 30.5 mmol) in THF (85 mL) at −78 °C under argon atmosphere, freshly crystallized N-bromosuccinimide (5.7 g, 32.0 mmol) was added. The mixture was stirred for 6 h at this temperature and warmed to rt. Pyridine (1 mL) was added and extracted with diethyl ether (2×50 mL). The combined organic layer was washed subsequently with water and brine and dried over anhydrous Na_2SO_4. Evaporation of solvent under reduced pressure gave the crude product. Purification by flash column chromatography (silica gel, 5% DCM/petroleum ether) afforded 1 h as colourless liquid (3.5 gm, 55%). The compound can be stored without appreciable decomposition for several months below 0 °C under argon atmosphere. R_f (10% DCM/Petroleum ether) 0.47; IR λ_{max} (KBr, cm^{-1}) 2925.3, 1483.9, 1462.0, 1422.0, 1359.3, 1322.3, 1238.8, 1155.0, 1128.5, 1106.3, 946.3, 764.7, 739.4; ^{1}H NMR (CDCl$_3$, 500 MHz, ppm). δ 7.68 (d, J=8 Hz, 1H), 7.38–7.29 (m, 3H), 7.06 (s, 1H), 3.73 (s, 3H); ^{13}C NMR (CDCl$_3$, 125 MHz, ppm). δ 136.3, 127.7, 127.3, 122.6, 120.1, 119.2, 109.7, 89.2, 32.9; Anal. Calcd for C_9H_8BrN: C, 51.46; H, 3.84; N, 6.67. Found: C, 52.48; H, 3.44; N, 6.25.

4.1.9. *3-(Diphenylphosphino)-1-methyl-1H-indole (L3).* To a stirred solution of 3-bromo-1-methyl-1H-indole (1h) (2.0 g, 6.3 mmol) in THF (25 mL) under argon atmosphere, was added n-BuLi (4.8 mL, 7.6 mmol, 1.6 M in THF) dropwise at −78 °C. The mixture was stirred for 2 h at −78 °C and chlorodiphenylphosphine (1.7 mL, 9.4 mmol, 1 M in THF) in THF (5 mL) was added dropwise at this temperature and stirred for further 4 h at −78 °C. It was slowly warmed to rt and quenched with saturated NH_4Cl solution at 0 °C. It was then extracted with diethyl ether (2×50 mL). The combined organic layer was washed subsequently with water and brine and dried over anhydrous Na_2SO_4. Evaporation of solvent under reduced pressure gave the crude product. Purification by flash column chromatography (silica gel, 15% dichloromethane/petroleum ether) afforded (L3) as white solid (1.75 g, 58%). R_f (10% EtOAc/Petroleum ether) 0.36; mp: 121 °C–123 °C; IR λ_{max} (KBr, cm^{-1}): 3055.4, 3039.9, 1506.5, 1460.2, 1433.2, 1329.0, 1238.3, 740.7, 694.4; ^{1}H NMR (CDCl$_3$, 500 MHz, ppm): δ 7.52–7.47 (m, 5H), 7.40–7.36 (m, 7H), 7.31 (t, J=7 Hz, 1H), 7.10 (t, J=7.5 Hz, 1H), 7.05 (d, J=3 Hz, 1H), 3.78 (s, 3H); ^{13}C NMR (CDCl$_3$, 125 MHz, ppm): δ 138.6, 137.9, 136.5, 136.2, 133.1, 133.0, 130.6, 130.5, 128.4, 128.4, 128.3, 122.2, 121.2, 121.2, 120.0, 109.7, 105.8, 33.0; ^{31}P NMR (CDCl$_3$, 202.44 MHz, ppm) δ −27.76 (s); HRMS (ESI) m/z calcd for $C_{21}H_{18}NP$ [M+H]$^+$: 316.1255, found 316.1250.

4.1.10. *3-(Diphenylphosphino)-1-tosyl-1H-indole (L4).* A mixture of 3-(diphenylphosphino)-1H-indole (301.1 mg, 1 mmol), TBAB (32.2 mg, 10 mol %), p-toluenesulfonyl chloride (286 mg, 1.5 mmol) in DCM (2 mL) was taken in a round bottomed flask under argon atmosphere and 0.5 mL of 50% NaOH solution was added dropwise with constant stirring. The stirring was continued upto 8 h. It was then extracted with diethyl ether (2×20 mL). The combined organic layer was washed subsequently with water and brine and dried

over anhydrous Na_2SO_4. Evaporation of solvent under reduced pressure gave the crude product. Purification by flash column chromatography (silica gel, 30% ethyl acetate/petroleum ether) afforded (L4) as white solid (310.4 mg, 68%). R_f (40% EtOAc/Petroleum ether) 0.52; mp: 63 °C–65 °C; IR λ_{max} (KBr, cm^{-1}): 3445.0, 3053.4, 1520.0, 1438.9, 1375.3, 1174.7, 1138.0, 1116.8, 1089.8, 947.1, 715.6, 540.1; ^{1}H NMR (CDCl$_3$, 500 MHz, ppm): δ 7.94 (d, J=8.5 Hz, 1H), 7.75–7.69 (m, 6H), 7.61 (d, J=5 Hz, 1H), 7.55 (t, J=7.5 Hz, 2H), 7.47–7.42 (m, 5H), 7.31 (t, J=8 Hz, 1H), 7.24 (d, J=8 Hz, 2H), 7.13 (t, J=8 Hz, 1H), 2.34 (s, 3H); ^{13}C NMR (CDCl$_3$, 125 MHz, ppm): δ 145.9, 135.8, 135.7, 134.6, 134.1, 133.9, 132.5, 132.4, 131.7, 131.7, 130.2, 130.1, 130.0, 128.8, 128.7, 127.1, 125.6, 124.2, 122.2, 114.0, 113.6, 113.1, 21.7; ^{31}P NMR (CDCl$_3$, 202.44 MHz, ppm): δ 21.53 (s); ^{31}P NMR (DMSO-d_6, 202.44 MHz, ppm): 19.82 (s); HRMS (ESI) m/z calcd for $C_{27}H_{22}NO_2PSK$ [M+K]$^+$: 494.0746 found 494.0746.

4.1.11. *tert-Butyl 3-(diphenylphosphino)-1H-indole-1-carboxylate (L5).* To a stirred solution of 3-(diphenylphosphino)-1H-indole (1e) (301.3 mg, 1 mmol) in DCM (2 mL) were successively added pyridine (0.1 mL, 1.3 mmol), (BOC)$_2$O (0.3 mL, 1.3 mmol), and DMAP (12.2 mg, 0.1 mmol). The mixture was stirred for 24 h at room temperature. Aqueous solution of NH_4Cl (2 mL) was added and the organic phase was separated. The aqueous phase was extracted with ethyl acetate (2×20 mL). The combined organic layers were dried over Na_2SO_4. The filtrate was concentrated in vacuo and the residue was purified by column chromatography (silica gel, 7% ethyl acetate/petroleum ether) to afford the compound (L5) (376.4 mg, 94%) as a colourless oil. R_f (10% EtOAc/Petroleum ether) 0.69; IR λ_{max} (KBr, cm^{-1}): 3068.9, 2978.2, 1736.0, 1450.5, 1369.5, 1356.0, 1305.9, 1248.0, 1153.5, 1060.9, 742.6; ^{1}H NMR (CDCl$_3$, 500 MHz, ppm): δ 8.14 (d, J=7 Hz, 1H), 7.43–7.39 (m, 5H), 7.34–7.31 (m, 8H), 7.12 (t, J=7 Hz, 1H), 1.65 (s, 9H); ^{13}C NMR (CDCl$_3$, 125 MHz, ppm): δ 149.5, 136.3, 136.2, 133.5, 133.3, 132.3, 132.1, 128.9, 128.7, 128.6, 124.7, 122.9, 121.4, 115.4, 84.3, 28.3; ^{31}P NMR (CDCl$_3$, 202.44 MHz, ppm): δ 17.99 (s); HRMS (ESI) m/z calcd for $C_{25}H_{24}NO_2PNa$ [M+Na]$^+$: 424.1442, found 424.1443.

4.1.12. *Procedure for synthesis of Pd–L1 complex (1f).* A solution of L1 (97.0 mg, 0.2 mmol) and Pd(CH$_3$CN)$_2$Cl$_2$ (52.0 mg, 0.2 mmol) in dichloromethane (4 mL) was stirred for 20 min at rt. The solvent was removed under reduced pressure. The residue was rinsed with hexane and dried in vacuo, affording 1f as a yellow-orange powder (120 mg, 91%), which was crystallized from dichloromethane/acetonitrile; mp>200 °C; Anal. Calcd for $C_{64}H_{50}Cl_4N_2P_4Pd_2$ C, 57.99; H, 3.80; N, 2.11. Found C, 57.71; H, 3.73; N, 2.05. The ^{1}H, ^{13}C and ^{31}P NMR spectra could not be recorded due to extremely poor solubility of the compound in solvents. After repeated attempts, a crystal suitable for diffraction studies was grown from dichloromethane/acetonitrile. Details of crystal structure determination are provided in the Supplementary data.

4.1.13. *Typical procedure for the cross-coupling reaction.* A solution of ligand (L1) (14.6 mg, 0.03 mmol), Pd(CH$_3$CN)$_2$Cl$_2$ (7.8 mg, 0.03 mmol), chloroarene (0.75 mmol), arylboronic acid (1.125 mmol), and NaOH (60 mg, 1.5 mmol) in DMA (1.0 mL) was stirred under argon atmosphere at 120 °C for 5–10 h (depending on the substrate). The reaction mixture was then cooled to rt, filtered through Celite and diluted with diethyl ether (20 mL). The organic layer was successively washed with cold water (3×10 mL) and brine and dried over anhydrous Na_2SO_4. The solvent was removed under reduced pressure and the residue was purified by flash chromatography on silica gel (230–400 mesh) with 1–10% ethyl acetate in petroleum ether or petroleum ether alone as eluent.

4.1.14. *4-Acetylbiphenyl (4a).*[5a] ^{1}H NMR (300 MHz, CDCl$_3$, ppm) δ 8.04 (d, J=8.4 Hz, 2H), 7.70–7.62 (m, 4H), 7.47–7.40 (m, 3H), 2.64

(s, 3H); ^{13}C NMR (75 MHz, CDCl$_3$, ppm) δ 197.8, 145.8, 139.9, 135.9, 129.0, 129.0, 128.3, 127.3, 127.3, 26.7.

4.1.15. 4-Nitrobiphenyl (4b).[5a] ^{1}H NMR (300 MHz, CDCl$_3$, ppm) δ 8.30 (d, J=8.7 Hz, 2H), 7.74 (d, J=8.7 Hz, 2H), 7.63 (dd, J=7.8, 1.4 Hz, 2H), 7.53–7.42 (m, 3H); ^{13}C NMR (75 MHz, CDCl$_3$, ppm) δ 147.7, 147.2, 138.9, 129.3, 129.0, 127.9, 127.5, 124.2.

4.1.16. 4-Cyanobiphenyl (4c).[5a] ^{1}H NMR (300 MHz, CDCl$_3$, ppm) δ 7.74–7.67 (m, 4H), 7.59 (dd, J=8.0, 1.6 Hz, 2H), 7.49–7.45 (m, 3H); ^{13}C NMR (75 MHz, CDCl$_3$, ppm) δ 145.7, 139.3, 132.7, 129.2, 128.8, 127.8, 127.3, 119.0, 111.0.

4.1.17. 4-Methoxybiphenyl (4d).[5a] ^{1}H NMR (300 MHz, CDCl$_3$, ppm) δ 7.48–7.43 (m, 4H), 7.32 (t, J=7.2 Hz, 2H), 7.21 (t, J=7.2 Hz, 1H), 6.89 (d, J=8.8 Hz, 2H), 3.75 (s, 3H); ^{13}C NMR (75 MHz, CDCl$_3$, ppm) δ 159.3, 140.9, 133.9, 128.9, 128.3, 126.9, 126.8, 114.3, 55.5.

4.1.18. 3-Methoxy-4′-methylbiphenyl (4e).[12] ^{1}H NMR (300 MHz, CDCl$_3$, ppm) δ 7.51 (d, J=8.1 Hz, 2H), 7.36 (t, J=7.9 Hz, 1H), 7.26 (d, J=7.9 Hz, 2H), 7.19–7.13 (m, 2H), 6.90 (d, J=6.9 Hz, 1H), 3.88 (s, 3H), 2.41 (s, 3H); ^{13}C NMR (75 MHz, CDCl$_3$, ppm) δ 160.1, 142.9, 138.4, 137.4, 129.8, 129.6, 127.2, 119.7, 112.9, 112.5, 55.4, 21.2.

4.1.19. 4-Methylbiphenyl (4f).[4e] ^{1}H NMR (300 MHz, CDCl$_3$, ppm) δ 7.60 (d, J=7.6 Hz, 2H), 7.53 (d, J=7.0 Hz, 2H), 7.44 (t, J=7.2 Hz, 2H), 7.35 (d, J=6.7 Hz, 1H), 7.26 (d, J=7.5 Hz, 2H), 2.41 (s, 3H); ^{13}C NMR (75 MHz, CDCl$_3$, ppm) δ 141.3, 138.5, 137.2, 129.7, 128.9, 127.2, 127.2, 21.3.

4.1.20. 2-Nitrobiphenyl (4g).[5a] ^{1}H NMR (300 MHz, CDCl$_3$) δ 7.85 (d, J=8.0 Hz, 1H), 7.62–7.59 (m, 1H), 7.48–7.41 (m, 5H), 7.35–7.32 (m, 2H); ^{13}C NMR (75 MHz, CDCl$_3$) δ 149.3, 137.4, 136.3, 132.4, 132.0, 128.7, 128.3, 128.2, 127.9, 124.1.

4.1.21. 1-Acetyl-4-phenylnaphthalene (4h).[13] ^{1}H NMR (300 MHz, CDCl$_3$, ppm) δ 8.10 (d, J=8.3 Hz, 2H), 7.94–7.84 (m, 3H), 7.63–7.42 (m, 6H), 2.69 (s, 3H); ^{13}C NMR (75 MHz, CDCl$_3$, ppm) δ 198.0, 145.9, 139.1, 136.1, 134.0, 131.3, 130.4, 128.6, 128.5, 127.1, 126.5, 126.1, 125.7, 125.5, 26.8.

4.1.22. 3-Phenylpyridine (4i).[5a] ^{1}H NMR (300 MHz, CDCl$_3$, ppm) δ 8.85 (s, 1H), 8.59 (d, J=3.2 Hz, 1H), 7.87 (d, J=7.6 Hz, 1H), 7.57 (d, J=6.9 Hz, 2H), 7.50–7.35 (m, 4H); ^{13}C NMR (75 MHz, CDCl$_3$, ppm) δ 148.5, 148.3, 137.9, 136.8, 134.5, 129.2, 128.2, 127.2, 123.7.

4.1.23. 3-Cyano-2-phenylpyridine (4j).[5a] ^{1}H NMR (300 MHz, CDCl$_3$, ppm) δ 8.86–8.84 (m, 1H), 8.07–8.04 (m, 1H), 7.94–7.91 (m, 2H), 7.53–7.51 (m, 3H), 7.37–7.34 (m, 1H); ^{13}C NMR (75 MHz, CDCl$_3$) δ 161.0, 152.7, 141.9, 137.2, 130.3, 128.9, 128.7, 121.6, 117.7, 107.5.

4.1.24. 2-Phenylpyridine (4k).[5a] ^{1}H NMR (300 MHz, CDCl$_3$, ppm) δ 8.73 (d, J=4.8 Hz, 1H), 8.02 (d, J=6.9 Hz, 2H), 7.78–7.76 (m, 2H), 7.53–7.44 (m, 3H), 7.26–7.19 (m, 1H); ^{13}C NMR (75 MHz, CDCl$_3$, ppm) δ 157.5, 149.6, 139.3, 137.0, 129.5, 128.8, 127.1, 122.2, 120.8.

4.1.25. 1-Benzyl-4-methoxybenzene (4l).[5a] ^{1}H NMR (300 MHz, CDCl$_3$, ppm) δ 7.23–7.18 (m, 2H), 7.13–7.09 (m, 3H), 7.03 (d, J=8.7 Hz, 2H), 6.76 (d, J=8.6 Hz, 2H), 3.86 (s, 2H), 3.71 (s, 3H); ^{13}C NMR (75 MHz, CDCl$_3$, ppm) δ 158.1, 141.7, 133.4, 130.0, 129.0, 128.6, 126.1, 114.0, 55.3, 41.2.

4.1.26. 1-[4-(Trifluoromethyl)benzyl]-4-methoxybenzene (4m).[11] ^{1}H NMR (300 MHz, CDCl$_3$) δ 7.43 (d, J=8.1 Hz, 2H), 7.18 (d, J=8.0 Hz, 2H), 7.00 (d, J=8.6 Hz, 2H), 6.76 (d, J=8.6 Hz, 2H), 3.88 (s, 2H), 3.69 (s, 3H); ^{13}C NMR (75 MHz, CDCl$_3$) δ 158.4, 145.9, 132.2, 130.0, 129.2, 128.5 (q, J=31.9 Hz), 125.5 (q, J=3.5 Hz), 124.5 (q, J=269.9 Hz), 114.2, 55.4, 41.0.

4.1.27. 1-(4-Fluorobenzyl)-4-methoxybenzene (4n).[11] ^{1}H NMR (300 MHz, CDCl$_3$) δ 7.18–7.10 (m, 4H), 6.99 (t, J=8.7 Hz, 2H), 6.87 (d, J=8.6 Hz, 2H), 3.92 (s, 2H), 3.81 (s, 3H); ^{13}C NMR (75 MHz, CDCl$_3$) δ 161.5 (d, J=242.2 Hz), 158.2, 137.4 (d, J=3.0 Hz), 133.2, 130.3 (d, J=7.8 Hz), 129.9, 115.3 (d, J=21.1 Hz), 114.1, 55.4, 40.3.

4.1.28. 1-(3-Chlorobenzyl)-4-methoxybenzene (4o).[11] ^{1}H NMR (300 MHz, CDCl$_3$) δ 7.26–7.24 (m, 3H), 7.17–7.11 (m, 3H), 6.91 (d, J=8.2 Hz, 2H), 3.95 (s, 2H), 3.84 (s, 3H); ^{13}C NMR (75 MHz, CDCl$_3$) δ 158.3, 143.8, 134.3, 132.4, 130.0, 129.8, 129.0, 127.1, 126.3, 114.1, 55.3, 40.8.

4.1.29. 1-(4-Methoxyphenyl)naphthalene (4p).[14] ^{1}H NMR (500 MHz, CDCl$_3$) δ 7.97–7.91 (m, 2H), 7.86 (d, J=8.5 Hz, 1H), 7.55–7.49 (m, 2H), 7.46–7.43 (m, 4H), 7.06 (d, J=8.5 Hz, 2H), 3.92 (s, 3H); ^{13}C NMR (125 MHz, CDCl$_3$) δ 159.1, 140.1, 134.0, 133.3, 132.0, 131.3, 128.4, 127.5, 127.0, 126.2, 126.1, 125.8, 125.5, 113.9, 55.5.

4.1.30. 1-(2-Methoxyphenyl)naphthalene (4q).[15] ^{1}H NMR (500 MHz, CDCl$_3$) δ 7.92–7.88 (m, 2H), 7.62 (d, J=8.5 Hz, 1H), 7.56 (t, J=7.0 Hz, 1H), 7.50–7.39 (m, 4H), 7.32 (d, J=8.5 Hz, 1H), 7.13–7.07 (m, 2H), 3.72 (s, 3H); ^{13}C NMR (125 MHz, CDCl$_3$) δ 157.4, 137.1, 133.6, 132.3, 132.1, 129.7, 129.1, 128.3, 127.8, 127.4, 126.6, 125.8, 125.7, 125.5, 120.7, 111.2, 55.7.

4.1.31. 4′-Methoxy-2,4,6-trimethylbiphenyl (4r).[16] ^{1}H NMR (500 MHz, CDCl$_3$) δ 7.08 (d, J=8.5 Hz, 2H), 6.99–6.96 (m, 4H), 3.88 (s, 3H), 2.35 (s, 3H), 2.04 (s, 6H); ^{13}C NMR (125 MHz, CDCl$_3$) δ 158.3, 138.8, 136.5, 133.5, 130.5, 128.2, 113.9, 55.3, 21.1, 20.9.

Acknowledgements

Supplementary data

Supplementary data (contains copies of ^{1}H and ^{13}C and ^{31}P NMR spectra of all products listed in the tables) associated with this article provided as a separate file. Crystallographic data (excluding structure factors) for the structures in this paper have been deposited with the Cambridge Crystallographic Data Centre as Supplementary publication nos CCDC No. 890817 for **L1** and CCDC No. 890818 for **1f**. Copies of data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: +44-(0)1223-336033 or e-mail: deposit@ccdc.cam.ac.uk). Supplementary data associated with this article can be found in online version.

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