Palladium-Catalyzed Intramolecular Direct Arylation for Phosphorus Heterocycle Synthesis

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Abstract: A palladium-catalyzed intramolecular direct arylation of bromo-substituted phosphine oxides is reported for the synthesis of phosphorus-containing heterocycles with good to excellent yields (78–98%)

Key words: C–H activation, direct arylation, palladium, phosphorus heterocycles

Transition-metal-catalyzed C–H bond activation reactions have gained considerable attention over the past decades because these processes do not require substrates bearing functionalized groups. Numerous methods have been developed for the synthesis of complex molecules from simple materials, which include various nitrogen- and oxygen-containing heterocycles.[1,2] In contrast, application of C–H activation strategies to the synthesis of phosphorus heterocycles has rarely been investigated, although phosphorus compounds are widely used materials in various fields, such as catalysis, pharmaceuticals, agrichemicals, and material chemistry.[3] Examples based on C–H bond activation strategies with palladium, ruthenium, or rhodium catalysts have only recently been reported for the construction of phosphorus-containing heterocycles.[4,5] In this paper, we describe a palladium-catalyzed intramolecular direct arylation reaction for the synthesis of phosphorus heterocycles with high yield.[6]

Initially, we chose *ortho*-bromophenyl diphenylphosphinate (**1a**) as the starting material. The expected coupled product could be easily converted into a diverse range of phosphorus compounds.[7] Palladium acetate was used as the metal catalyst for the current reaction. After screening various reaction parameters, including solvents, ligands, and bases (Table 1, entries 1–16), the highest product yield was 54% (entry 16), which occurred with complete consumption of **1a**. The possible reason for this moderate yield may be the decomposition of substrate **1a** under the reaction conditions. We then investigated the use of alternative substrates for the current reaction. Substrate **1b**, with one more carbon atom than **1a**, did not produce the corresponding arylation product (entry 17). In contrast, with the oxygen atom in **1a** replaced by a carbon atom, substrate **1c** was found to be a good candidate, yielding the desired product with approximately the same quantitative yield as that obtained with the combination of simple triphenylphosphine as the ligand and potassium carbonate as the base (entry 18).

With the optimum conditions determined, the scope of substrates was explored; the results are shown in Scheme 1. Substrates bearing either electron-rich or electron-poor groups, such as methoxy, alkyl, and halide groups, can be employed to afford the corresponding products in high yields. More sterically hindered substrates require higher temperature (130 °C) to achieve high conversion (**2j** and **2k**). Attempts to develop an asymmetric variant of the current reaction remain unsuccessful. Various chiral ligands, such as mono- or bisphosphine, phosphoramidate, and N-heterocyclic carbene,[8] were examined, but the products were always isolated in racemic form (Scheme 2), which may be attributed to the high flexibility of the carbon linker of substrate **1c**.

Competition experiments with substrates bearing different moieties were conducted, and the results show that electron-deficient substrates have higher reactivity than electron-rich substrates (Scheme 3), which is consistent with the phenomenon observed in the concerted metalation–deprotonation (CMD) pathway.[9] On this basis, a proposed mechanism for the current reaction is shown in Scheme 4. Oxidative addition of the aryl bromide bond to palladium(0) initially occurs to generate a palladium(II) aryl intermediate. The bromide is then replaced by a pivalate anion, followed by an intramolecular CMD step, affording intermediate **C**. Finally, reductive elimination of **C** from the palladium(II) atom releases the coupling product and regenerates the palladium(0) active catalyst (Scheme 4).

In conclusion, a palladium-catalyzed intramolecular direct arylation of bromo-substituted phosphine oxides was developed, yielding six-membered phosphorus heterocycles in high yields.

Commercially available reagents were used without further purification. Solvents were treated prior to use according to the standard methods. Melting points were determined using an SGW X-4 melting point apparatus and are uncorrected. ^{1}H NMR, ^{13}C NMR and ^{31}P NMR spectra were recorded at r.t. in $CDCl_3$ with a Varian 400 MHz spectrometer using tetramethylsilane as internal standard. Flash column chromatography was performed on silica gel (300–400 mesh).

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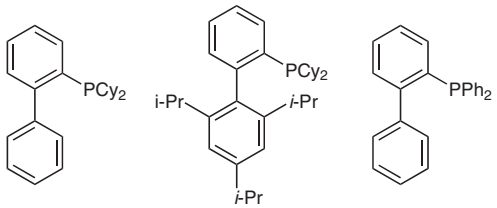
Table 1 Effect of Solvents, Bases, and Ligands[a]

Entry	Substrate	Ligand	Base	Solvent	Temp (°C)	Time (h)	Yield (%)[b]
1	**1a**	Ph_3P	K_3PO_4	DMA	55	8	0
2	**1a**	Ph_3P	K_2CO_3	DMA	55	8	43
3	**1a**	Ph_3P	Na_2CO_3	DMA	55	8	30
4	**1a**	Ph_3P	PivOK	DMA	55	8	10
5	**1a**	Ph_3P	AcOK	DMA	55	8	0
6	**1a**	Ph_3P	K_2CO_3	THF	55	8	0
7	**1a**	Ph_3P	K_2CO_3	DCE	55	8	0
8	**1a**	Ph_3P	K_2CO_3	DMF	55	8	9
9	**1a**	Ph_3P	K_2CO_3	toluene	55	8	0
10	**1a**	**L1**	K_2CO_3	DMA	55	8	11
11	**1a**	**L2**	K_2CO_3	DMA	55	8	14
12	**1a**	**L3**	K_2CO_3	DMA	55	8	0
13	**1a**	*t*-Bu_3P	K_2CO_3	DMA	55	8	0
14	**1a**	binap	K_2CO_3	DMA	55	8	0
15	**1a**	Ph_3P	K_2CO_3	toluene/DMA(1:1)	55	8	27
16	**1a**	Ph_3P	K_2CO_3	toluene/DMA (1:2)	55	8	54
17	**1b**	Ph_3P	K_2CO_3	DMA	100	24	0
18	**1c**	Ph_3P	K_2CO_3	DMA	60	20	98



[a] Reaction conditions: **1** (0.20 mmol), $Pd(OAc)_2$ (10 mol%), ligand (10 mol%), base (0.60 mmol), solvent (3 mL).
[b] Isolated yield.

Intramolecular Arylation of Bromo-Substituted Phosphine Oxides; General Procedure

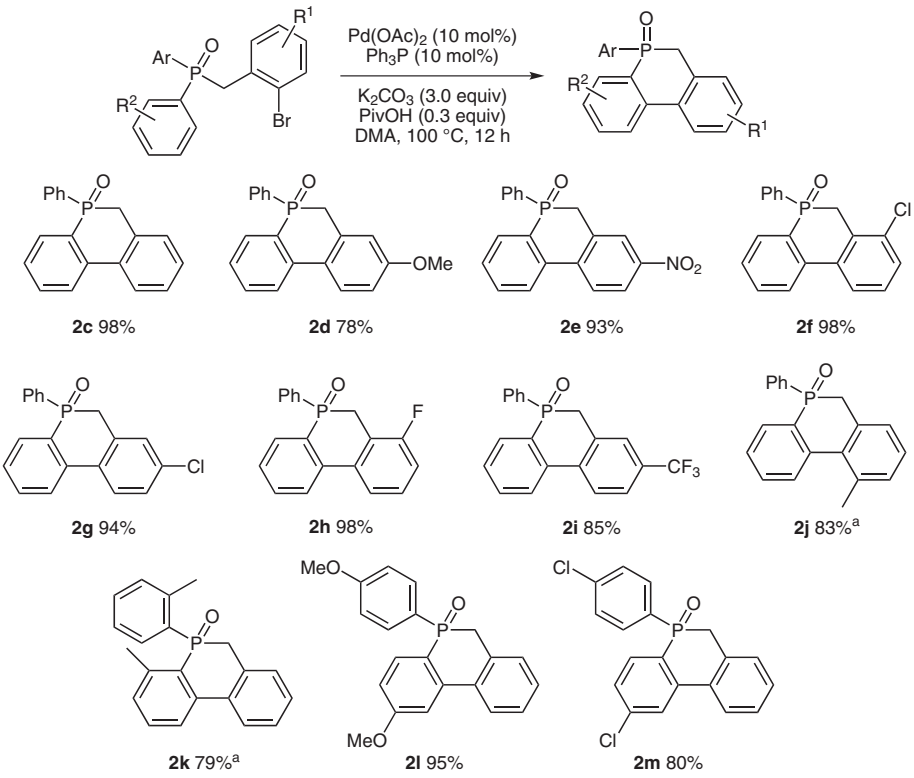
Phosphine oxide (0.20 mmol), palladium acetate (4.5 mg, 0.020 mmol), triphenylphosphine (5.2 mg, 0.020 mmol), and pivalic acid (6.2 mg, 0.060 mmol) were dissolved in dimethyl acetamide (2 mL) under a nitrogen atmosphere, and the resulting mixture was stirred at 100 °C for 12 h. After cooling to r.t., the mixture was filtered over Celite and concentrated under vacuum. The residue was purified by silica gel chromatography (CH_2Cl_2–EtOAc) to recover the product as a white solid.

9,10-Dihydro-9-oxa-10-phenyl-10-phosphaphenanthrene-10-oxide (2a)

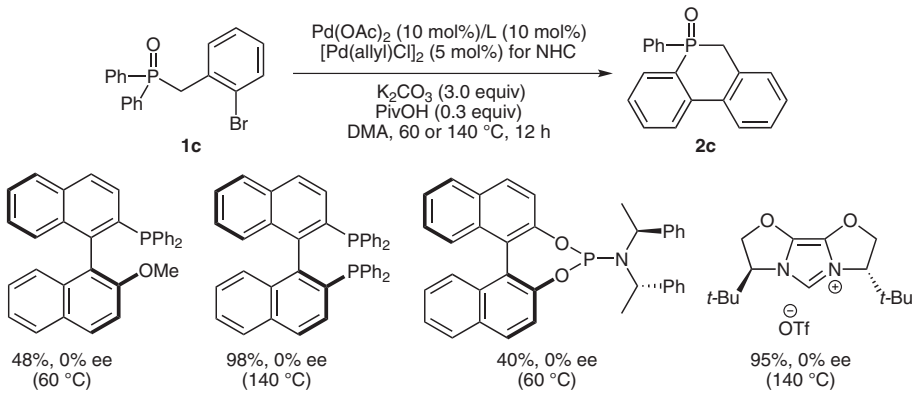
Yield: 32.8 mg (54%); white solid; mp 172–174 °C.

FTIR (neat): 3055, 2947, 2885, 1589, 1557, 1473, 1435, 1392, 1312, 1223, 1192, 1154, 1115, 1071, 832, 803, 746, 727, 716, 694 cm^{-1}.

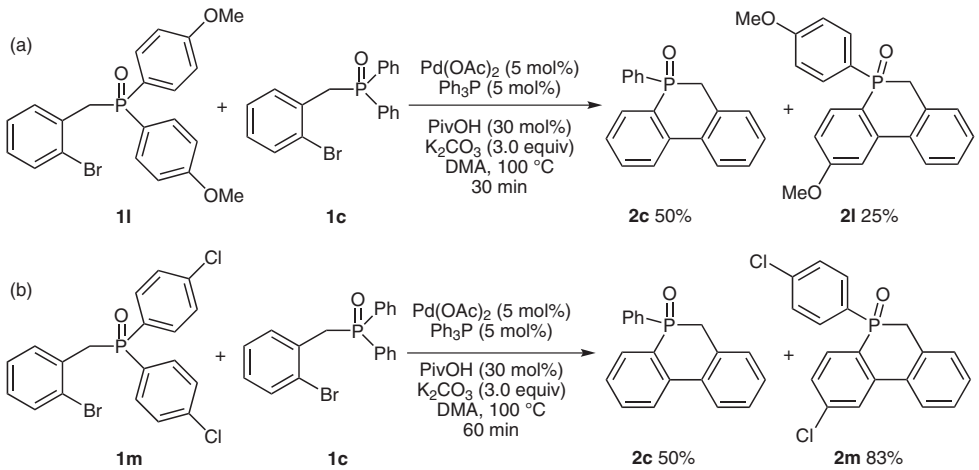
^1H NMR (400 MHz, $CDCl_3$): δ = 8.04 (dd, *J* = 8.0, 4.8 Hz, 1 H), 7.99 (dd, *J* = 8.0, 1.2 Hz, 1 H), 7.86–7.79 (m, 2 H), 7.68 (t, *J* = 8.0 Hz, 1 H), 7.63–7.56 (m, 2 H), 7.50–7.36 (m, 4 H), 7.29–7.24 (m, 2 H).



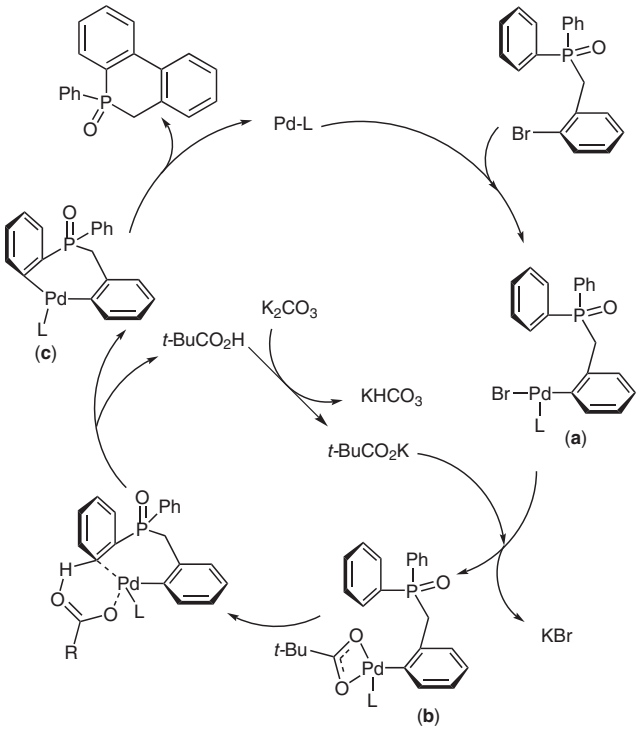
Scheme 1 Reaction scope. *Reagents and conditions*: phosphine oxide (0.20 mmol), $Pd(OAc)_2$ (10 mol%), Ph_3P (10 mol%), K_2CO_3 (0.60 mmol), DMA (3 mL), 100 °C, 12 h; isolated yields given. [a] Reactions were conducted at 130 °C.



Scheme 2 Investigations with chiral ligands



Scheme 3 Competition experiments



Scheme 4 Proposed catalytic pathway

$^{31}P\{^{1}H\}$ NMR (162 MHz, $CDCl_3$): δ = 25.3 (s).

5,6-Dihydro-5-phenyl-phosphanthridine 5-Oxide (2c)
Yield: 56.8 mg (98%); white solid; mp 119–121 °C.

FTIR (neat): 3055, 2947, 2885, 1589, 1557, 1473, 1435, 1392, 1312, 1223, 1192, 1154, 1115, 1071, 832, 803, 746, 727, 716, 694 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.93 (dd, *J* = 12.0, 7.2 Hz, 1 H), 7.84 (dd, *J* = 8.0, 4.8 Hz, 1 H), 7.74 (d, *J* = 7.6 Hz, 1 H), 7.64 (t, *J* = 8.0 Hz, 1 H), 7.54–7.49 (m, 2 H), 7.48–7.42 (m, 1 H), 7.40–7.32 (m, 2 H), 7.31–7.25 (m, 2 H), 7.20 (t, *J* = 7.2 Hz, 1 H), 7.14 (d, *J* = 7.6 Hz, 1 H), 3.69 (dd, *J* = 21.2, 16.0 Hz, 1 H), 3.43 (dd, *J* = 16.0, 14.0 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 140.0 (d, J_{C-P} = 7.5 Hz), 134.1 (d, J_{C-P} = 10.0 Hz), 132.9 (d, J_{C-P} = 2.6 Hz), 131.7 (d, J_{C-P} = 2.6 Hz), 131.25 (d, J_{C-P} = 10.1 Hz), 131.20 (d, J_{C-P} = 101.8 Hz), 130.8 (d, J_{C-P} = 7.1 Hz), 130.6 (d, J_{C-P} = 9.6 Hz), 129.2 (d, J_{C-P} = 6.4 Hz), 128.8, 128.3 (d, J_{C-P} = 1.9 Hz), 128.2 (d, J_{C-P} = 11.9 Hz), 128.1 (d, J_{C-P} = 11.2 Hz), 128.0 (d, J_{C-P} = 99.2 Hz), 126.5 (d, J_{C-P} = 2.2 Hz), 125.7 (d, J_{C-P} = 9.3 Hz), 34.2 (d, J_{C-P} = 69.6 Hz).

$^{31}P\{^{1}H\}$ NMR (162 MHz, $CDCl_3$): δ = 21.8 (s).

HRMS (ESI): *m*/*z* $[M]^+$ calcd for $C_{19}H_{15}OP$: 290.0861; found: 290.0863.

5,6-Dihydro-8-methoxy-5-phenyl-phosphanthridine 5-Oxide (2d)
Yield: 50.1 mg (78%); white solid; mp 159–161 °C.

FTIR (neat): 3077, 3050, 3005, 2962, 2917, 2879, 2831, 1606, 1590, 1504, 1465, 1436, 1315, 1230, 1182, 1145, 1117, 1105, 1077, 1033, 938, 861, 839, 820, 771, 756, 745, 718, 709, 698 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.88 (ddd, *J* = 12.4, 7.6, 1.2 Hz, 1 H), 7.75 (dd, *J* = 8.0, 4.8 Hz, 1 H), 7.67 (d, *J* = 8.8 Hz, 1 H), 7.60 (t, *J* = 8.0 Hz, 1 H), 7.56–7.50 (m, 2 H), 7.41–7.36 (m, 2 H), 7.31–7.26 (m, 2 H), 6.87 (dd, *J* = 8.8, 2.4 Hz, 1 H), 6.68 (d, *J* = 2.4 Hz, 1 H), 3.75 (s, 3 H), 3.67 (dd, *J* = 20.8, 16.0 Hz, 1 H), 3.38 (dd, *J* = 16.0, 14.0 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 159.5 (d, J_{C-P} = 0.7 Hz), 140.0 (d, J_{C-P} = 7.3 Hz), 132.9 (d, J_{C-P} = 2.4 Hz), 131.7 (d, J_{C-P} = 2.7 Hz), 131.2 (d, J_{C-P} = 101.6 Hz), 130.8 (d, J_{C-P} = 5.8 Hz), 130.7 (d, J_{C-P} = 6.6 Hz), 130.6 (d, J_{C-P} = 9.7 Hz), 128.2 (d, J_{C-P} = 12.0 Hz), 127.9 (d, J_{C-P} = 2.7 Hz), 127.2 (d, J_{C-P} = 11.2 Hz), 127.0 (d, J_{C-P} = 100.4 Hz), 126.8 (d, J_{C-P} = 10.0 Hz), 125.1 (d, J_{C-P} = 9.3 Hz), 116.4 (d, J_{C-P} = 10.0 Hz), 113.7 (d, J_{C-P} = 1.5 Hz), 55.1, 34.4 (d, J_{C-P} = 69.3 Hz).

$^{31}P\{^{1}H\}$ NMR (162 MHz, $CDCl_3$): δ = 22.7 (s).

HRMS (ESI): *m*/*z* $[M]^+$ calcd for $C_{20}H_{17}O_2P$: 320.0966; found: 320.0960.

5,6-Dihydro-8-nitro-5-phenyl-phosphanthridine 5-Oxide (2e)
Yield: 65.1 mg (93%); white solid; mp 183–185 °C.

FTIR (neat): 3062, 2960, 2916, 1563, 1436, 1335, 1184, 1115, 1104, 1027, 927, 908, 844, 830, 810, 750, 740, 724, 708, 691 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.21 (d, *J* = 8.8 Hz, 1 H), 8.08 (d, *J* = 2.0 Hz, 1 H), 7.98–7.91 (m, 3 H), 7.77 (t, *J* = 7.6 Hz, 1 H), 7.60 (t, *J* = 7.6 Hz, 1 H), 7.58–7.46 (m, 3 H), 7.39–7.35 (m, 2 H), 3.77 (dd, *J* = 20.4, 16.0 Hz, 1 H), 3.38 (dd, *J* = 16.0, 13.6 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 147.1, 140.0 (d, J_{C-P} = 9.6 Hz), 137.9 (d, J_{C-P} = 7.1 Hz), 133.5 (d, J_{C-P} = 2.2 Hz), 132.4 (d, J_{C-P} = 2.6 Hz), 131.41 (d, J_{C-P} = 6.7 Hz), 131.37 (d, J_{C-P} = 6.3 Hz), 130.8 (d, J_{C-P} = 10.0 Hz), 130.04 (d, J_{C-P} = 103.8 Hz), 130.01 (d, J_{C-P} = 11.2 Hz), 128.7 (d, J_{C-P} = 11.9 Hz), 128.6 (d, J_{C-P} = 99.4 Hz), 127.6 (d, J_{C-P} = 2.2 Hz), 126.8 (d, J_{C-P} = 8.9 Hz), 126.1 (d, J_{C-P} = 10.0 Hz), 123.4 (d, J_{C-P} = 1.5 Hz), 34.3 (d, J_{C-P} = 69.4 Hz).

$^{31}P\{^{1}H\}$ NMR (162 MHz, $CDCl_3$): δ = 20.3 (s).

HRMS (ESI): *m*/*z* $[M]^+$ calcd for $C_{19}H_{14}NO_3P$: 335.0711; found: 335.0686.

5,6-Dihydro-7-chloro-5-phenyl-phosphanthridine 5-Oxide (2f)
Yield: 63.6 mg (98%); white solid; mp 165–167 °C.

FTIR (neat): 3069, 3055, 2991, 2883, 1589, 1552, 1475, 1439, 1419, 1233, 1196, 1158, 1142, 1119, 1076, 842, 830, 811, 797, 752, 726 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.97 (dd, *J* = 12.0, 7.6 Hz, 1 H), 7.82 (dd, *J* = 7.6, 5.2 Hz, 1 H), 7.70–7.64 (m, 2 H), 7.56–7.50 (m, 3 H), 7.43 (t, *J* = 7.2 Hz, 1 H), 7.36–7.23 (m, 4 H), 3.99 (dd, *J* = 16.0, 14.8 Hz, 1 H), 3.60 (dd, *J* = 20.0, 16.0 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 139.6 (d, J_{C-P} = 7.8 Hz), 136.2 (d, J_{C-P} = 10.7 Hz), 135.3 (d, J_{C-P} = 9.3 Hz), 133.0 (d, J_{C-P} = 2.6 Hz), 132.0 (d, J_{C-P} = 2.6 Hz), 130.81 (d, J_{C-P} = 6.7 Hz), 130.80 (d, J_{C-P} = 103.2 Hz), 129.4 (d, J_{C-P} = 1.1 Hz), 128.7 (d, J_{C-P} = 3.4 Hz), 128.6 (d, J_{C-P} = 6.0 Hz), 128.4 (d, J_{C-P} = 12.3 Hz), 127.8 (d, J_{C-P} = 100.6 Hz), 127.7 (d, J_{C-P} = 4.6 Hz), 126.4 (d, J_{C-P} = 9.2 Hz), 125.3 (d, J_{C-P} = 2.2 Hz), 123.4 (d, J_{C-P} = 1.5 Hz), 29.6 (d, J_{C-P} = 70.5 Hz).

$^{31}P\{^{1}H\}$ NMR (162 MHz, $CDCl_3$): δ = 22.1 (s).

HRMS (ESI): *m*/*z* $[M]^+$ calcd for $C_{19}H_{14}ClOP$: 324.0471; found: 324.0463.

5,6-Dihydro-8-chloro-5-phenyl-phosphanthridine 5-Oxide (2g)
Yield: 61.1 mg (94%); white solid; mp 156–158 °C.

FTIR (neat): 3099, 3055, 3021, 2866, 1589, 1551, 1472, 1435, 1381, 1192, 1142, 1128, 1110, 885, 834, 825, 787, 765, 755, 739, 732, 713, 690, 651 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.92 (dd, *J* = 12.0, 7.6 Hz, 1 H), 7.82 (dd, *J* = 7.6, 4.8 Hz, 1 H), 7.71–7.64 (m, 2 H), 7.57–7.42 (m, 4 H), 7.37–7.31 (m, 3 H), 7.18 (d, *J* = 1.6 Hz, 1 H), 3.67 (dd, *J* = 20.8, 16.0 Hz, 1 H), 3.42 (dd, *J* = 16.0, 13.6 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 139.0 (d, J_{C-P} = 7.4 Hz), 134.3, 133.1 (d, J_{C-P} = 2.6 Hz), 132.7 (d, J_{C-P} = 10.0 Hz), 132.0 (d, J_{C-P} = 2.6 Hz), 131.1 (d, J_{C-P} = 10.4 Hz), 131.0 (d, J_{C-P} = 1.5 Hz), 130.9 (d, J_{C-P} = 4.8 Hz), 130.69 (d, J_{C-P} = 101.4 Hz), 130.67 (d, J_{C-P} =

9.6 Hz), 128.5, 128.42 (d, J_{C-P} = 8.5 Hz), 128.41 (d, J_{C-P} = 12.4 Hz), 127.8 (d, J_{C-P} = 2.2 Hz), 127.7 (d, J_{C-P} = 99.9 Hz), 125.7 (d, J_{C-P} = 9.3 Hz), 34.0 (d, J_{C-P} = 69.4 Hz).

$^{31}P\{^1H\}$ NMR (162 MHz, $CDCl_3$): δ = 21.8 (s).

HRMS (ESI): *m/z* $[M]^+$ calcd for $C_{19}H_{14}ClOP$: 324.0471; found: 324.0464.

5,6-Dihydro-7-fluoro-5-phenyl-phosphanthridine 5-Oxide (2h)
Yield: 60.4 mg (98%); white solid; mp 137–138 °C.

FTIR (neat): 3062, 2953, 2918, 2849, 1611, 1589, 1557, 1452, 1435, 1391, 1240, 1223, 1199, 1185, 1147, 1134, 1117, 1094, 887, 859, 832, 804, 768, 748, 721, 695, 665 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.97 (ddd, *J* = 12.4, 7.2, 1.2 Hz, 1 H), 7.86 (dd, *J* = 7.6, 4.8 Hz, 1 H), 7.69 (t, *J* = 7.6 Hz, 1 H), 7.58–7.49 (m, 4 H), 7.43 (td, *J* = 7.6, 4.8 Hz, 1 H), 7.35–7.28 (m, 3 H), 7.02 (t, *J* = 8.4 Hz, 1 H), 3.72 (dd, *J* = 16.4, 14.0 Hz, 1 H), 3.47 (dd, *J* = 20.4, 16.4 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 160.5 (dd, J_{C-F} = 245.3 Hz, J_{C-P} = 8.3 Hz), 139.4 (d, *J* = 7.2, 3.1 Hz), 136.1 (d, *J* = 10.6, 3.4 Hz), 133.1 (d, J_{C-P} = 2.5 Hz), 132.0 (d, J_{C-P} = 3.0 Hz), 131.1 (d, J_{C-P} = 6.8 Hz), 131.0 (d, J_{C-P} = 103.5 Hz), 130.6 (d, J_{C-P} = 9.9 Hz), 129.0 (d, *J* = 9.1, 1.9 Hz), 128.7 (d, J_{C-P} = 11.0 Hz), 128.5 (d, J_{C-P} = 12.9 Hz), 127.9 (d, J_{C-P} = 100.0 Hz), 126.2 (d, J_{C-P} = 8.7 Hz), 122.1 (d, *J* = 3.0, 2.3 Hz), 116.9 (d, *J* = 17.8, 5.3 Hz), 115.5 (d, *J* = 23.2, 0.8 Hz), 24.7 (d, *J* = 61.6, 4.6 Hz).

$^{31}P\{^1H\}$ NMR (162 MHz, $CDCl_3$): δ = 22.0 (s).

HRMS (ESI): *m/z* $[M]^+$ calcd for $C_{19}H_{14}FOP$: 308.0766; found: 308.0760.

5,6-Dihydro-8-trifluoromethyl-5-phenyl-phosphanthridine 5-Oxide (2i)
Yield: 60.9 mg (85%); white solid; mp 269–271 °C.

FTIR (neat): 3068, 2869, 1615, 1591, 1437, 1412, 1385, 1334, 1315, 1270, 1217, 1192, 1168, 1140, 1118, 1105, 1081, 1019, 930, 851, 837, 794, 781, 766, 743, 713, 695, 654 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 8.01 (s, 1 H), 7.92–7.88 (m, 2 H), 7.73 (t, *J* = 8.0 Hz, 1 H), 7.58–7.42 (m, 5 H), 7.38–7.30 (m, 3 H), 3.73 (dd, *J* = 20.8, 16.0 Hz, 1 H), 3.47 (dd, *J* = 16.0, 13.6 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 138.8 (d, J_{C-P} = 27.4 Hz), 135.9 (d, J_{C-P} = 10.0 Hz), 133.5 (dd, *J* = 6.7, 1.5 Hz), 133.4 (d, J_{C-P} = 2.2 Hz), 132.2 (d, J_{C-P} = 2.6 Hz), 131.8 (d, J_{C-P} = 9.7 Hz), 131.2 (d, J_{C-P} = 7.1 Hz), 130.82 (d, J_{C-P} = 10.0 Hz), 130.80 (dd, *J* = 32.6, 1.9 Hz), 130.6 (d, J_{C-P} = 103.3 Hz), 129.1 (d, J_{C-P} = 11.2 Hz), 128.6 (d, J_{C-P} = 12.3 Hz), 128.1 (d, J_{C-P} = 99.5 Hz), 126.1 (d, J_{C-P} = 9.3 Hz), 125.3 (q, *J* = 3.7 Hz), 123.8 (q, J_{C-F} = 273.1 Hz), 123.5 (m), 34.4 (d, J_{C-P} = 69.0 Hz).

$^{31}P\{^1H\}$ NMR (162 MHz, $CDCl_3$): δ = 20.9 (s).

HRMS (ESI): *m/z* $[M]^+$ calcd for $C_{20}H_{14}F_3OP$: 358.0734; found: 358.0726.

5,6-Dihydro-10-methyl-5-phenyl-phosphanthridine 5-Oxide (2j)
Yield: 50.5 mg (83%); white solid; mp 158–159 °C.

FTIR (neat): 3055, 2986, 2943, 2873, 1587, 1574, 1557, 1471, 1447, 1434, 1208, 1171, 1156, 1141, 1116, 845, 809, 784, 770, 753, 746, 727, 694 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.99 (dd, *J* = 12.8, 8.0 Hz, 1 H), 7.66–7.62 (m, 2 H), 7.50–7.44 (m, 3 H), 7.39 (d, *J* = 6.8 Hz, 1 H), 7.29–7.25 (m, 2 H), 7.20 (d, *J* = 7.6 Hz, 1 H), 7.08 (t, *J* = 7.6 Hz, 1 H), 6.98 (d, *J* = 7.6 Hz, 1 H), 3.58 (dd, *J* = 20.0, 15.6 Hz, 1 H), 3.34 (t, *J* = 15.2 Hz, 1 H), 2.54 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 139.5 (d, J_{C-P} = 7.5 Hz), 135.4 (d, J_{C-P} = 2.6 Hz), 134.2 (d, *J* = 9.6 Hz), 131.8 (d, J_{C-P} = 2.2 Hz), 131.6 (d, J_{C-P} = 2.6 Hz), 131.4 (d, J_{C-P} = 2.3 Hz), 130.8 (d, J_{C-P} = 7.0 Hz), 130.6 (d, J_{C-P} = 9.6 Hz), 130.5 (d, *J* = 102.1 Hz), 130.0 (d, J_{C-P} = 8.9 Hz), 129.9 (d, J_{C-P} = 101.0 Hz), 129.5 (d, J_{C-P} = 7.1 Hz), 128.5 (d, J_{C-P} = 8.9 Hz), 128.1 (d, J_{C-P} = 10.4 Hz), 128.0, 127.5 (d, *J* = 10.2 Hz), 35.3 (d, J_{C-P} = 69.5 Hz), 22.6.

$^{31}P\{^1H\}$ NMR (162 MHz, $CDCl_3$): δ = 23.2 (s).

HRMS (ESI): *m/z* $[M]^+$ calcd for $C_{20}H_{17}OP$: 304.1017; found: 304.1010.

4-Methyl-5,6-dihydro-5-(2-methylphenyl)phosphanthridine 5-Oxide (2k)
Yield: 50.3 mg (79%); white solid; mp 60–63 °C.

FTIR (neat): 3052, 3010, 2923, 2893, 2848, 1586, 1557, 1449, 1381, 1281, 1239, 1192, 1158, 1134, 1072, 1030, 874, 834, 803, 753, 678 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.67 (dd, *J* = 8.0, 4.4 Hz, 1 H), 7.58–7.53 (m, 2 H), 7.30–7.10 (m, 6 H), 7.05 (d, *J* = 7.6 Hz, 1 H), 6.96 (t, *J* = 7.2 Hz, 1 H), 3.72 (dd, *J* = 21.2, 16.0 Hz, 1 H), 3.51 (dd, *J* = 15.6, 12.8 Hz, 1 H), 2.66 (s, 3 H), 2.60 (s, 3 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 143.8 (d, J_{C-P} = 6.3 Hz), 141.5 (d, J_{C-P} = 7.4 Hz), 141.4 (d, *J* = 8.6 Hz), 135.0 (d, J_{C-P} = 10.4 Hz), 132.7 (d, J_{C-P} = 1.3 Hz), 132.1 (d, J_{C-P} = 12.6 Hz), 131.75, 131.68 (d, J_{C-P} = 7.8 Hz), 131.2 (d, J_{C-P} = 10.0 Hz), 130.1 (d, *J* = 9.3 Hz), 129.2 (d, J_{C-P} = 97.6 Hz), 129.0 (d, J_{C-P} = 6.6 Hz), 128.4, 128.1 (d, J_{C-P} = 1.9 Hz), 127.5 (d, J_{C-P} = 2.6 Hz), 125.9 (d, J_{C-P} = 99.5 Hz), 125.3 (d, *J* = 12.6 Hz), 124.3 (d, J_{C-P} = 9.0 Hz), 34.7 (d, J_{C-P} = 69.7 Hz), 22.1 (d, J_{C-P} = 4.9 Hz), 21.1 (d, J_{C-P} = 3.7 Hz).

$^{31}P\{^1H\}$ NMR (162 MHz, $CDCl_3$): δ = 25.7 (s).

HRMS (ESI): *m/z* $[M + H]^+$ calcd for $C_{21}H_{20}OP$: 319.1246; found: 319.1249.

2-Methoxy-5,6-dihydro-5-(4-methoxyphenyl)-phosphanthridine 5-Oxide (2l)
Yield: 66.5 mg (95%); white solid; mp 62–64 °C.

FTIR (neat): 3052, 3010, 2923, 2893, 2848, 1586, 1557, 1449, 1239, 1192, 1158, 1134, 834, 803, 753, 678, 642 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.82 (dd, *J* = 12.0, 8.4 Hz, 1 H), 7.73 (d, *J* = 7.6 Hz, 1 H), 7.43 (dd, *J* = 7.6, 4.8 Hz, 2 H), 7.36–7.30 (m, 2 H), 7.22 (t, *J* = 7.6 Hz, 1 H), 7.15 (d, *J* = 7.6 Hz, 1 H), 6.98 (dd, *J* = 8.4, 0.8 Hz, 1 H), 6.80 (dd, *J* = 8.8, 2.0 Hz, 2 H), 3.91 (s, 3 H), 3.74 (s, 3 H), 3.64 (dd, *J* = 20.4, 16.0 Hz, 1 H), 3.38 (dd, *J* = 16.0, 14.0 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 163.0 (d, J_{C-P} = 2.7 Hz), 162.0 (d, J_{C-P} = 2.7 Hz), 141.7 (d, *J* = 8.3 Hz), 133.8 (d, J_{C-P} = 9.9 Hz), 132.5 (d, J_{C-P} = 7.6 Hz), 132.3 (d, J_{C-P} = 10.0 Hz), 131.1 (d, J_{C-P} = 9.8 Hz), 129.7 (d, J_{C-P} = 6.5 Hz), 128.6, 128.0 (d, *J* = 1.5 Hz), 126.2 (d, J_{C-P} = 1.9 Hz), 122.2 (d, J_{C-P} = 108.7 Hz), 119.5 (d, J_{C-P} = 106.1 Hz), 113.6 (d, J_{C-P} = 12.9 Hz), 112.9 (d, J_{C-P} = 11.8 Hz), 111.7 (d, *J* = 9.9 Hz), 55.1, 54.8, 34.3 (d, J_{C-P} = 70.8 Hz).

$^{31}P\{^1H\}$ NMR (162 MHz, $CDCl_3$): δ = 19.6 (s).

HRMS (ESI): *m/z* $[M + H]^+$ calcd for $C_{21}H_{20}O_3P$: 351.1145; found: 351.1149.

2-Chloro-5,6-dihydro-5-(4-chlorophenyl)phosphanthridine 5-Oxide (2m)
Yield: 57.4 mg (80%); white solid; mp 80–82 °C.

FTIR (neat): 3055, 2944, 2873, 1643, 1580, 1546, 1480, 1437, 1384, 1222, 1195, 1159, 1119, 1085, 1013, 884, 810, 786, 766, 745, 720, 694, 632, 624, 607 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.90–7.84 (m, 2 H), 7.73 (d, *J* = 8.0 Hz, 1 H), 7.48–7.38 (m, 4 H), 7.30–7.25 (m, 3 H), 7.18 (d, *J* = 8.0 Hz, 1 H), 3.73 (dd, *J* = 21.2, 16.4 Hz, 1 H), 3.59 (dd, *J* = 16.0, 14.0 Hz, 1 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 142.0 (d, J_{C-P} = 8.0 Hz), 139.9 (d, *J* = 3.4 Hz), 138.7 (d, J_{C-P} = 3.5 Hz), 133.1 (d, J_{C-P} = 9.5 Hz), 132.5

(d, J_{C-P} = 7.2 Hz), 132.1 (d, J_{C-P} = 10.3 Hz), 131.6 (d, J_{C-P} = 10.3 Hz), 129.8, 129.45 (d, J = 102.6 Hz), 129.40 (d, J_{C-P} = 6.5 Hz), 128.87 (d, J_{C-P} = 12.5 Hz), 128.86 (d, J_{C-P} = 1.9 Hz), 128.5 (d, J_{C-P} = 1.8 Hz), 126.8 (d, J_{C-P} = 2.7 Hz), 126.4 (d, J = 9.5 Hz), 126.1 (d, J_{C-P} = 101.1 Hz), 34.2 (d, J_{C-P} = 70.2 Hz).

$^{31}P\{^{1}H\}$ NMR (162 MHz, $CDCl_3$): δ = 21.1 (s).

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{19}H_{14}Cl_2OP$: 359.0154; found: 359.0154.

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Supporting Information for this article is available online at http://www.thieme-connect.com/ejournals/toc/synthesis.

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