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# Copper-Catalyzed Cascade Phosphorylation Initiated Radical Cyclization: Access to 2-Phosphorylated Pyrrolo[1,2-*a*]indole

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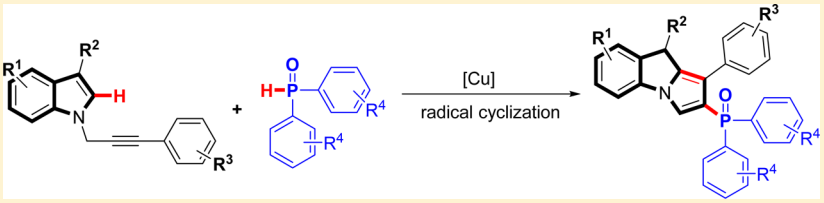
Supporting Information




**ABSTRACT:** A copper-catalyzed tandem radical cyclization of 1-(3-phenylprop-2-yn-1-yl)-1*H*-indole with diphenylphosphine oxides was developed. C−P bond formation was achieved coupled with C($sp^2$)−H functionalization. It provided an access to construct the pyrrolo[1,2-*a*]indole motif and a series of 2-phosphinoyl-9*H*-pyrrolo[1,2-*a*]indoles.

Polycyclic indole is one of important heterocycle classes, because of their biological and pharmacological activities.[1] For example, pyrrolo[1,2-*a*]indoles are important frameworks, which are present in numerous natural products and pharmaceutical chemicals, such as apo-Mitomycin B, Mitosene Lactam, and protein kinase C-â inhibitor JTT-010 (Scheme 1).[2] There have been several methods to construct the pyrrolo[1,2-*a*]indole scaffold.[3] Very recently, an effective silver-mediated tandem phosphinoylation/cyclization process to construct 2-phosphinoyl-9*H*-pyrrolo[1,2-*a*] indoles was developed by the Zhao and Tang group.[3c] An expensive transition-metal catalyst and high temperature are usually needed in these strategies. However, this motif remains interesting to organic synthetic chemists.[3]

Phosphonates are widely found in organic chemicals such as functional materials,[4] natural products,[5] and pharmaceutical chemicals.[6] Because of their special bioactivities,[6] it is of great importance to develop methods for the construction of the C−P bond. Enormous efforts have been devoted to phosphorylation reactions catalyzed by transition metals[7] or under metal-free conditions.[8] A variety of tandem reactions initiated by the addition of P-centered radicals to active alkenes were reported, providing a useful strategy to construct organophosphorus frameworks especially heterocycles.[9] Our group reported a silver-catalyzed cascade radical 6-endo-trig cyclization initiated by phosphorylation of *N*-methyl-*N*-phenylcinnamamides.[10] However, only several cascade reactions of P-centered radicals with alkynes through C−H functionalization were reported to date.[11] Thus, it remains a challenge to explore efficient P-centered radical cascade reactions, which would provide an alternative strategy for synthesis of organophosphorus compounds. As our continuous research, herein, we report a copper-catalyzed cascade phosphorylation initiated radical cyclization, providing an access to 2-phosphorylated-pyrrolo-[1,2-*a*]indole.

The initial studies were carried out by selecting 3-methyl-1-(3-phenylprop-2-yn-1-yl)-1*H*-indole (**1a**) as a model substrate to react with diphenylphosphine oxide in the presence of 20 mol % $Cu(OAc)_2$ and 2 equiv of $K_2S_2O_8$ in 2 mL of MeCN at 60 °C for 12 h under an Ar atmosphere. To our delight, (9-methyl-1-phenyl-9*H*-pyrrolo[1,2-*a*]indol-2-yl)-diphenyl-phosphine oxide (**3a**) was obtained in 42% yield (Table 1, entry 1). Different metal catalysts were screened, and anhydrous $CuSO_4$ exhibited the best catalytic activity with a 52% yield of **3a** (Table 1, entries 1−5). Oxidants were tested, and no better result was obtained (Table 1, entries 6−9), indicating that $K_2S_2O_8$ is the most suitable oxidant. As 25 mol % anhydrous $CuSO_4$ was loaded, **3a** was generated in 76% yield (Table 1, entry 10). However, increasing the amount of $CuSO_4$ did not result in an increase in yield (Table 1, entry 11). Similarly, the yield decreased to 62% when 3 equiv $K_2S_2O_8$ were loaded (Table 1, entry 12). When the reactions were carried out under higher or lower temperature, the yield decreased (Table 1, entries 13, 14), showing that 60 °C is the most suitable reaction temperature. Without $CuSO_4$, **3a** was obtained only in 15% yield (Table 1, entry 15). A trace of **3a** was obtained when no $K_2S_2O_8$ was loaded (Table 1, entry 16). This result showed that $CuSO_4$ is of great importance for this transformation.

As the optimized reaction conditions were estiblished, it was applied to a series of 1-(3-phenylprop-2-yn-1-yl)-1*H*-indoles.

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**Scheme 1. Pyrrolo[1,2-*a*]indole Derivatives**

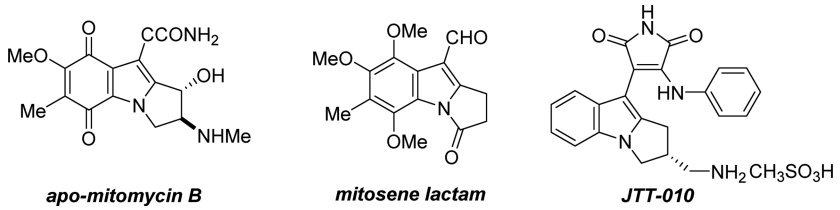
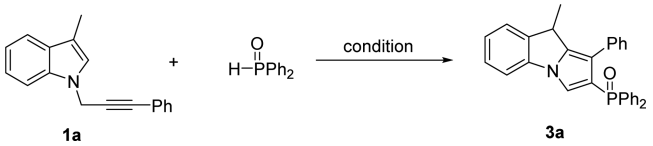



**Table 1. Optimization of Reaction Condition**[a]




| entry | catalyst (mol %) | oxidant (equiv) | *T* (°C) | yield of **3a** (%)[b] |
|---|---|---|---|---|
| 1 | $Cu(OAc)_2$ (20) | $K_2S_2O_8$ (2) | 60 | 42 |
| 2 | $CuSO_4$ (20) | $K_2S_2O_8$ (2) | 60 | 52 |
| 3 | $Cu(OTf)_2$ (20) | $K_2S_2O_8$ (2) | 60 | 30 |
| 4 | $Fe(NO_3)_3$ (20) | $K_2S_2O_8$ (2) | 60 | trace |
| 5[c] | – | $AgNO_3$ (2) | 60 | 35 |
| 6 | $CuSO_4$ (20) | $(NH_4)_2S_2O_8$ (2) | 60 | 30 |
| 7 | $CuSO_4$ (20) | $Na_2S_2O_8$ (2) | 60 | 46 |
| 8 | $CuSO_4$ (20) | DDQ (2) | 60 | trace |
| 9 | $CuSO_4$ (20) | DTBP (2) | 60 | trace |
| 10 | $CuSO_4$ (25) | $K_2S_2O_8$ (2) | 60 | 76 |
| 11 | $CuSO_4$ (30) | $K_2S_2O_8$ (2) | 60 | 57 |
| 12 | $CuSO_4$ (25) | $K_2S_2O_8$ (3) | 60 | 62 |
| 13 | $CuSO_4$ (25) | $K_2S_2O_8$ (2) | 70 | 66 |
| 14 | $CuSO_4$ (25) | $K_2S_2O_8$ (2) | 50 | 36 |
| 15 | – | $K_2S_2O_8$ (2) | 60 | 15 |
| 16 | $CuSO_4$ (25) | – | 60 | trace |

[a]Reaction condition: **1a** (0.1 mmol), diphenylphosphine oxide (0.2 mmol), MeCN (2 mL), under an Ar atmosphere, 12 h unless otherwise noted. [b]Isolated yield. [c]DMF(2 mL) was used.

The results showed that both electron- and electron-donating functional groups were well tolerated (Figure 1). The corresponding products could be also obtained in moderate yield when indoles were substituted by chlorine atoms (Figure 1, **3d**). It provided the possibility for further transformation of these products. When substituent groups (such as Me, OMe, $OCF_3$, F, Ac, *t*Bu) were on the phenyl ring attached to a carbon−carbon triple bond, the reaction efficiency was nearly unaffected, generating the desired products in moderate to good yield (Figure 1, **3f**−**3n**). Diphenylphosphine oxides substituted by Me, OMe, or Br were also scoped, and the corresponding products were obtained in moderate yields (Figure 1, **3o**−**3x**). When the phenyl ring attached to the carbon−carbon triple bond was replaced by a thiophene ring, product **3u** was generated in 38% yield (Figure 1, **3u**). However, it did not work when a methyl group was used (Figure 1, **3v**). Diethyl phosphite and dibenzyl phosphite also could not react with 1-(3-phenylprop-2-yn-1-yl)-1*H*-indole (Figure 1, **3w**−**3x**). Furthermore, a gram-scale reaction of **1b** and diphenylphosphine oxide was performed, generating product **3b** in 65% yield (Figure 2).

For further investagation of the mechanism, some control experiments were carried out. When 1 equiv of radical inhibitor 2,2,6,6-tetramethylpiperidine oxide (TEMPO) was loaded, the reaction ceased and no **3a** was detected (Scheme 2). The TEMPO-$P(O)Ph_2$ adduct was observed by LC-MS (mass calcd for $C_{21}H_{29}NO_2P$ $[M + H]^+$: 358.18, found 358.92) and $^{31}P$ NMR ($\delta$ 33.5).[12] Meanwhile, an EPR experiment was conducted to detected the P-centered radical by addition of 2-methyl-2-nitrosopropane (MNP), a radical spin trapping agent. When MNP was added to the reaction system, an EPR signal was recorded (Scheme 3(b)). It showed that a P-centered radical generated and trapped by MNP, forming a relatively stable radical A ($a_N$ = 10.56 G, $a_P$ = 12.02 G).[13] The result suggested that this reaction undergoes a radical pathway.

On the basis of above results and previous literature reports,[14] we suggested a plausible mechanism (Scheme 4). First, a P-centered radical formed when diphenylphosphine oxide was oxidized by Cu(II) and Cu(I) was released.[14a] Oxidized by $K_2S_2O_8$, Cu(I) transformed to Cu(II). Then, a vinyl radical **I** was generated after the addition of the P-centered radical to the C−C triple bond.[14b] Radical intermediate **II** was afforded, as vinyl radical **I** underwent a intramolecular cyclization.[14c] Oxidized by $K_2S_2O_8$ or Cu(II), radical **II** transformed to be cation **III**.[14a] Finally, deprotonation of the cation **III** generated intermediate **IV**,[14c] which transformed to the final product **3b** through an isomerization process.

In conclusion, we have reported a copper catalyzed tandom C−H functionalization/radical cyclization initiated by phosphorylation. In this reaction, both P−H and C−H bonds were activated. A direct access to 2-phosphorylated-pyrrolo[1,2-*a*]indoles was provided. A series of functional groups were well tolerated, giving the corresponding products in moderate to good yields. Meanwhile, a method to synthesize polycyclic indoles was developed, which may be applied in organic synthetic chemistry.

## EXPERIMENTAL SECTION

**General Information.** All reagents were purchased from chemical supliers and used without further purification.

1-(3-Phenylprop-2-yn-1-yl)-1*H*-indoles were prepared according to literature reports.[11c,15] The radical cyclization was performed under an Ar atmosphere. The reaction was detected by TLC. The products were separated by TLC. HRMS data were carried out by a TOF LC-MS. $^1H$, $^{19}F$, $^{31}P$, and $^{13}C$ NMR spectra were recorded using a 400 MHz spectrometer using $CDCl_3$ as solvent.

**Experimental Procedure for the Copper-Catalyzed Cyclization of 1-(3-Phenylprop-2-yn-1-yl)-1*H*-indole with Diphenylphosphine Oxide.** 1-(3-Phenylprop-2-yn-1-yl)-1*H*-indole (0.1 mmol), diphenylphosphine oxide (0.2 mmol, 2.0 equiv), $CuSO_4$ (0.025 mmol, 25 mol %), $K_2S_2O_8$ (0.2 mmol, 2.0 equiv), MeCN (2.0 mL), and a stir bar were added to a sealed tube under an Ar atmosphere. Then the tube was heated to 60 °C for 12 h. The tube was cooled to room temperature, and the mixture was concentraed in vacuum. The corresponding product **3** was separated by TLC using ethyl acetate and petroleum (1:1−2:1) as solvents.

*(9-Methyl-1-phenyl-9H-pyrrolo[1,2-a]indol-2-yl)diphenylphosphine Oxide (**3a**).* Mp: 194.1−196.4 °C, light yellow solid (33.6 mg, 76%). $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 7.83−7.76 (m, 2H), 7.70−



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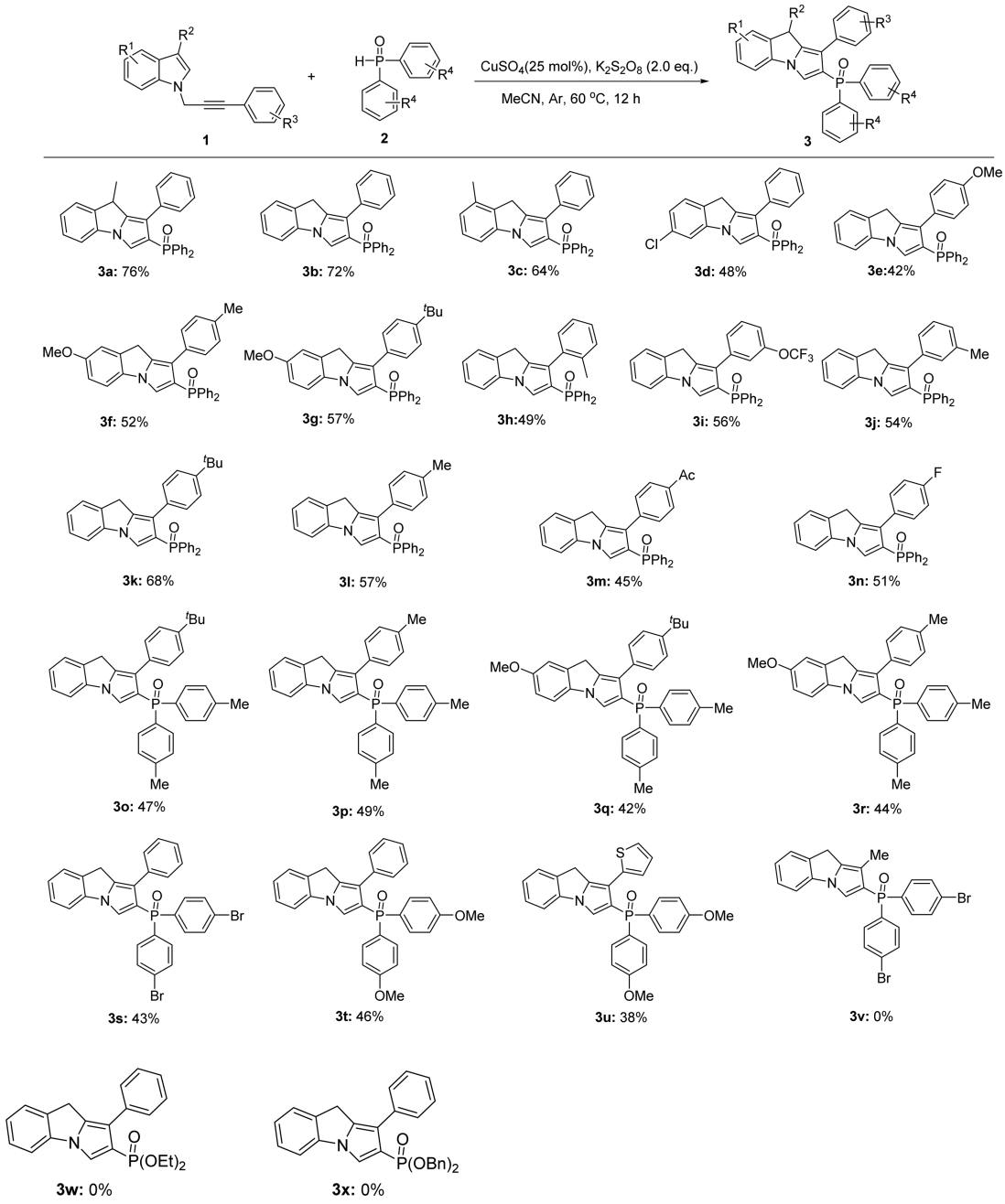



**Figure 1.** Copper-catalyzed tandom cyclization of 1-(3-phenylprop-2-yn-1-yl)-1*H*-indoles with diphenylphosphine oxide. Standard condition: 1-(3-phenylprop-2-yn-1-yl)-1*H*-indole (0.1 mmol), diphenylphosphine oxide (0.2 mmol), anhydrous $CuSO_4$ (25 mol %), $K_2S_2O_8$ (2.0 equiv), MeCN (2.0 mL), 60 °C, 12 h under an Ar atmosphere. The isolated yield is provided.

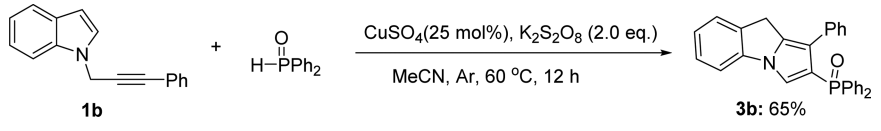
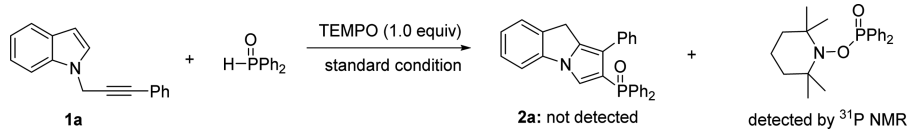



**Figure 2.** Gram-scale reaction.

## Scheme 2. Radical Trapping Experiment



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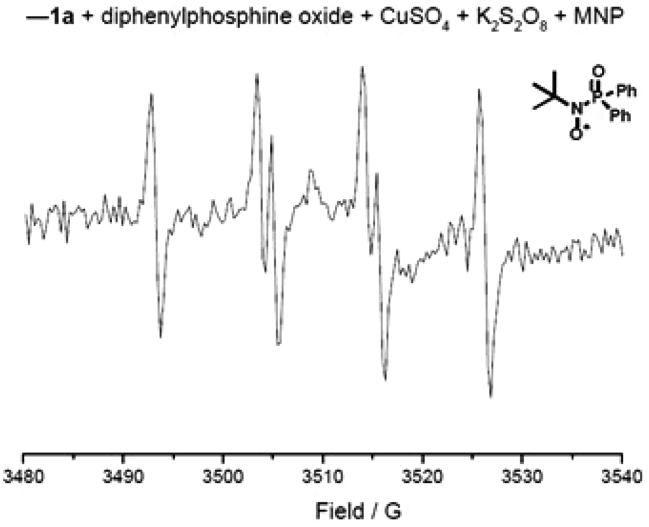
**Scheme 3. EPR Experiment**[a]




[a]The electron paramagnetic resonance (EPR) spectra (X band, 0.5 GHz, room temperature) of the reaction mixture of **1a**, diphenylphosphine oxide, $CuSO_4$, and $K_2S_2O_8$ in MeCN at 60 °C

7.63 (m, 2H), 7.53 (d, *J* = 7.2 Hz, 2H), 7.50−7.47 (m, 1H), 7.45−7.40 (m, 2H), 7.37 (d, *J* = 7.4 Hz, 1H), 7.34−7.15 (m, 7H), 7.11 (t, *J* = 7.5 Hz, 2H), 7.03 (t, *J* = 7.3 Hz, 1H), 6.94 (d, *J* = 3.9 Hz, 1H), 4.34 (q, *J* = 7.1 Hz, 1H), 1.31 (d, *J* = 7.2 Hz, 3H). $^{13}$C NMR (100 MHz, $CDCl_3$) δ 140.7, 140.5, 140.4, 138.8, 134.0 (d, *J* = 107.0 Hz), 133.8, 133.5, 132.8, 131.9, 131.8, 131.7, 131.3, 131.3, 131.2, 131.1, 129.3, 128.2, 128.1, 128.0, 127.8, 127.7, 126.3, 125.0, 124.8, 122.2, 122.1, 118.8, 118.6, 118.3, 117.1, 110.4, 36.2, 17.1. $^{31}$P NMR (162 MHz, $CDCl_3$) δ 21.10. HRMS (ESI) calcd for $C_{30}H_{24}NNaOP^+$ (M + $Na^+$): 468.1488, found: 468.1484.

*Diphenyl(1-phenyl-9H-pyrrolo[1,2-a]indol-2-yl)phosphine Oxide (**3b**).* Mp: 259.5−262.0 °C, light yellow solid (30.9 mg, 72%). $^1$H NMR (400 MHz, $CDCl_3$) δ 7.79−7.71 (m, 4H), 7.64−7.57 (m, 2H), 7.42 (m, 3H), 7.38−7.28 (m, 6H), 7.23 (d, *J* = 7.5 Hz, 1H), 7.19−7.13 (m, 3H), 7.04 (t, *J* = 7.4 Hz, 1H), 6.96 (d, *J* = 4.0 Hz, 1H), 4.02 (s, 2H). $^{13}$C NMR (100 MHz, $CDCl_3$) δ 139.7, 135.4, 135.3, 134.5, 134.2, 133.8 (d, *J* = 107.3 Hz), 131.9, 131.8, 131.3, 131.3, 128.7, 128.3, 128.2, 128.0, 127.7, 126.2, 126.1, 124.7, 121.9, 121.9, 119.5, 119.3, 117.9, 116.8, 110.6, 29.6. $^{31}$P NMR (162 MHz, $CDCl_3$) δ 21.33. HRMS (ESI) calcd for $C_{29}H_{22}NNaOP^+$ (M + $Na^+$): 454.1331, found:454.1326.

*(8-Methyl-1-phenyl-9H-pyrrolo[1,2-a]indol-2-yl)diphenylphosphine Oxide (**3c**).* Mp: 236.4−238.6 °C, light yellow solid (28.3 mg, 64%). $^1$H NMR (400 MHz, $CDCl_3$) δ 7.79−7.71 (m, 4H), 7.63−7.60 (m, 2H), 7.45−7.40 (m, 2H), 7.37−7.32 (m, 4H), 7.22 (t, *J* = 7.7 Hz, 1H), 7.16 (t, *J* = 7.6 Hz, 2H), 7.10−7.04 (m, 2H), 7.01 (t, *J* = 7.2 Hz, 1H), 6.94 (d, *J* = 4.0 Hz, 1H), 3.92 (s, 2H), 2.36 (s, 3H). $^{13}$C NMR (100 MHz, $CDCl_3$)δ 139.4, 135.9, 135.3, 134.9 (d, *J* = 109.5 Hz), 133.3, 131.9, 131.8, 131.3, 131.3, 128.7, 128.1, 128.0, 127.8, 126.1, 125.8, 119.6, 119.3, 108.0, 28.6, 18.5. $^{31}$P NMR (162 MHz, $CDCl_3$) δ 21.47. HRMS (ESI) calcd for $C_{30}H_{24}NNaOP^+$ (M + $Na^+$): 468.1488, found: 468.1493.

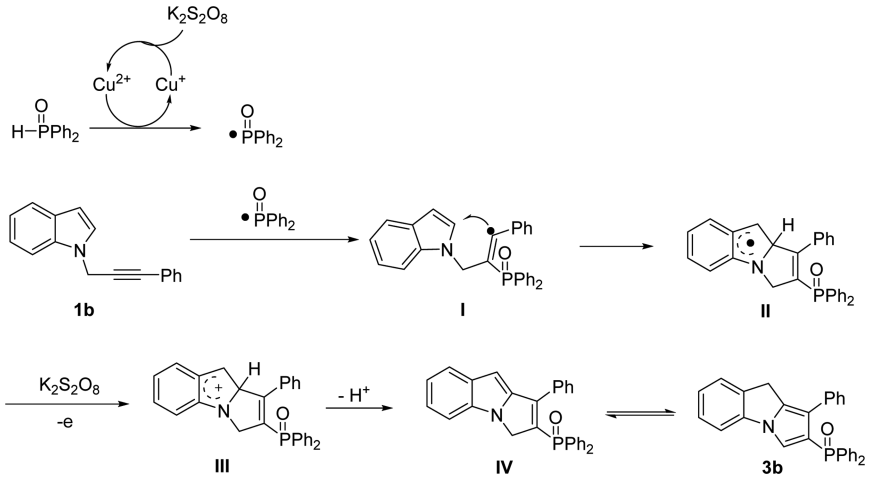
*(6-Chloro-1-phenyl-9H-pyrrolo[1,2-a]indol-2-yl)diphenylphosphine Oxide (**3d**).* Mp: 281.5−283.2 °C, light yellow solid (25.5 mg, 48%). $^1$H NMR (400 MHz, $CDCl_3$) δ 7.77−7.71 (m, 4H), 7.60 (d, *J* = 7.4 Hz, 2H), 7.44−7.41 (m, 2H), 7.38−7.33 (m, 5H), 7.23 (d, *J* = 1.7 Hz, 1H), 7.18−7.13 (m, 3H), 7.07−7.03 (m, 1H), 6.89 (d, *J* = 3.9 Hz, 1H), 3.99 (s, 2H). $^{13}$C NMR (100 MHz, $CDCl_3$) δ 140.6, 133.8, 133.6, 133.5 (d, *J* = 107.2 Hz), 131.9, 131.8, 131.4, 128.7, 128.2, 128.1, 127.0, 126.3, 124.6, 119.5, 119.3, 111.3, 29.2. $^{31}$P NMR (162 MHz, $CDCl_3$) δ 21.10. HRMS (ESI) calcd for $C_{29}H_{21}NClNaOP^+$ (M + $Na^+$): 488.0941, found: 488.0943.

*(1-(4-Methoxyphenyl)-9H-pyrrolo[1,2-a]indol-2-yl)diphenylphosphine Oxide (**3e**).* Mp: 133.9−135.1 °C, light yellow solid (19.2 mg, 42%). $^1$H NMR (400 MHz, $CDCl_3$) δ 7.76−7.71 (m, 4H), 7.51 (d, *J* = 8.7 Hz, 2H), 7.43 (dd, *J* = 7.8, 1.9 Hz, 3H), 7.38−7.34 (m, 4H), 7.29 (d, *J* = 7.2 Hz, 1H), 7.23 (d, *J* = 7.7 Hz, 1H), 7.17 (dd, *J* = 7.9, 7.0 Hz, 1H), 6.93 (d, *J* = 3.9 Hz, 1H), 6.70 (d, *J* = 8.7 Hz, 2H), 3.99 (s, 2H), 3.72 (s, 3H). $^{13}$C NMR (100 MHz, $CDCl_3$) δ 157.9, 139.8, 134.9, 134.6, 133.8 (d, *J* = 107.2 Hz), 131.9, 131.8, 131.3, 129.9, 128.2, 128.0, 127.7, 126.8, 126.2, 124.6, 119.2, 119.0, 113.5, 110.5, 55.2, 29.5. $^{31}$P NMR (162 MHz, $CDCl_3$) δ 21.47. HRMS (ESI) calcd for $C_{30}H_{24}NNaO_2P^+$ (M + $Na^+$): 484.1437, found: 484.1439.

*(7-Methoxy-1-(p-tolyl)-9H-pyrrolo[1,2-a]indol-2-yl)diphenylphosphine Oxide (**3f**).* Mp: 153.4−155.6 °C, light yellow solid (24.5 mg, 52%). $^1$H NMR (400 MHz, $CDCl_3$) δ 7.77−7.71 (m, 4H), 7.48−7.41 (m, 4H), 7.37−7.32 (m, 4H), 7.13 (d, *J* = 8.5 Hz, 1H), 7.00 (d, *J* = 1.9 Hz, 1H), 6.95 (d, *J* = 7.9 Hz, 2H), 6.87 (d, *J* = 3.8 Hz, 1H), 6.83−6.79 (m, 1H), 3.98 (s, 2H), 3.82 (s, 3H), 2.22 (s, 3H). $^{13}$C NMR (100 MHz, $CDCl_3$) δ 157.3, 136.2, 135.6, 135.1, 135.0, 133.9 (d, *J* = 107.1 Hz), 133.7, 132.0, 131.9, 131.2, 131.2, 128.7, 128.6, 128.1, 128.0, 122.0, 119.2, 119.0, 112.6, 112.5, 110.9, 55.8, 29.8, 21.1. $^{31}$P NMR (162 MHz, $CDCl_3$) δ 21.83. HRMS (ESI) calcd for $C_{31}H_{27}NO_2P^+$ (M + $H^+$): 476.1774, found: 476.1777.

*(1-(4-(tert-Butyl)phenyl)-7-methoxy-9H-pyrrolo[1,2-a]indol-2-yl)diphenylphosphine Oxide (**3g**).* Mp: 116.3−118.7 °C, light yellow solid (29.2 mg, 57%). $^1$H NMR (400 MHz, $CDCl_3$) δ 7.74 (dd, *J* = 12.1, 7.1 Hz, 4H), 7.45−7.37 (m, 4H), 7.35−7.30 (m, 4H), 7.15−7.10 (m, 3H), 7.00 (d, *J* = 1.9 Hz, 1H), 6.92 (d, *J* = 3.7 Hz, 1H), 6.83−6.79 (m, 1H), 3.98 (s, 2H), 3.82 (s, 3H), 1.22 (s, 9H). $^{13}$C NMR (100

**Scheme 4. Plausible Reaction Mechanism**



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MHz, $CDCl_3$) $\delta$ 157.3, 148.8, 136.2, 134.9, 134.8, 133.8 (d, $J$ = 107.3 Hz), 133.7, 132.0, 131.9, 131.2, 131.2, 128.4, 128.1, 128.0, 124.8, 121.9, 121.9, 119.1, 118.9, 116.9, 115.7, 112.6, 112.5, 110.9, 55.8, 34.3, 31.2, 29.7. $^{31}P$ NMR (162 MHz, $CDCl_3$) $\delta$ 21.49. HRMS (ESI) calcd for $C_{34}H_{32}NNaO_2P^+$ (M + $Na^+$): 540.2063, found: 540.2057.

*Diphenyl(1-(o-tolyl)-9H-pyrrolo[1,2-a]indol-2-yl)phosphine Oxide (**3h**).* Mp: 216.3−217.9 °C, light yellow solid (21.7 mg, 49%). $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 7.63 (s, 4H), 7.40 (d, $J$ = 7.1 Hz, 4H), 7.35−7.27 (m, 6H), 7.19−7.15 (m, 1H), 7.12 (d, $J$ = 7.4 Hz, 1H), 7.02 (t, $J$ = 7.4 Hz, 1H), 6.95−6.88 (m, 2H), 3.67 (s, 2H), 1.95 (s, 3H). $^{13}C$ NMR (100 MHz, $CDCl_3$) $\delta$ 140.01, 137.16, 135.42, 134.79, 133.02, 131.78, 131.67, 131.16, 129.33, 127.97, 127.85, 127.78, 127.24, 126.23, 124.95, 124.50, 120.38, 118.33, 110.64, 28.93, 19.84. $^{31}P$ NMR (162 MHz, $CDCl_3$) $\delta$ 21.64. HRMS (ESI) calcd for $C_{30}H_{25}NOP^+$ (M + $H^+$): 446.1668, found: 446.1662.

*Diphenyl(1-(3-(trifluoromethoxy)phenyl)-9H-pyrrolo[1,2-a]indol-2-yl)phosphine Oxide (**3i**).* Mp: 195.3−196.7 °C, light yellow solid (28.6 mg, 56%). $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 7.79−7.72 (m, 4H), 7.64 (d, $J$ = 7.8 Hz, 1H), 7.47−7.42 (m, 4H), 7.39−7.34 (m, 4H), 7.31 (d, $J$ = 7.6 Hz, 1H), 7.25−7.13 (m, 3H), 6.95 (d, $J$ = 4.0 Hz, 1H), 6.89 (d, $J$ = 8.2 Hz, 1H), 4.02 (s, 2H). $^{13}C$ NMR (100 MHz, $CDCl_3$) $\delta$ 148.9, 139.5, 136.3, 136.0, 135.9, 134.3, 133.3 (d, $J$ = 107.5 Hz), 131.9, 131.8, 131.5, 131.5, 129.4, 128.2, 128.1, 127.8, 127.5, 126.3, 124.9, 121.7, 120.8, 120.5, 120.4, 119.6, 119.4, 118.5, 118.2, 117.1, 110.7, 29.5. $^{19}F$ NMR (376 MHz, $CDCl_3$) $\delta$ −57.63. $^{31}P$ NMR (162 MHz, $CDCl_3$) $\delta$ 20.93. HRMS (ESI) calcd for $C_{30}H_{21}F_3NNaO_2P^+$ (M + $Na^+$): 538.1154, found: 538.1150.

*Diphenyl(1-(m-tolyl)-9H-pyrrolo[1,2-a]indol-2-yl)phosphine Oxide (**3j**).* Mp: 278.2−280.5 °C, light yellow solid (23.8 mg, 54%). $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 7.79−7.73 (m, 4H), 7.45−7.41 (m, 3H), 7.38−7.33 (m, 6H), 7.30 (d, $J$ = 7.4 Hz, 1H), 7.24 (d, $J$ = 7.6 Hz, 1H), 7.19−7.15 (m, 1H), 7.04 (t, $J$ = 7.6 Hz, 1H), 7.00 (d, $J$ = 4.0 Hz, 1H), 6.85 (d, $J$ = 7.5 Hz, 1H), 4.01 (s, 2H), 2.18 (s, 3H). $^{13}C$ NMR (100 MHz, $CDCl_3$) $\delta$ 139.7, 137.4, 135.2, 134.6, 134.0, 133.9 (d, $J$ = 107.1 Hz), 131.9, 131.8, 131.6, 131.2, 129.8, 128.4, 128.1, 128.0, 127.9, 127.7, 126.9, 126.7, 126.2, 125.5, 124.6, 119.4, 119.2, 110.6, 29.6, 21.3. $^{31}P$ NMR (162 MHz, $CDCl_3$) $\delta$ 21.04. HRMS (ESI) calcd for $C_{30}H_{25}NOP^+$ (M + $H^+$) 446.1668, found: 446.1673.

*(1-(4-(tert-Butyl)phenyl)-9H-pyrrolo[1,2-a]indol-2-yl)diphenylphosphine Oxide (**3k**).* Mp: 138.4−143.7 °C, light yellow solid (32.9 mg, 68%). $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 7.77−7.71 (m, 4H), 7.46−7.39 (m, 5H), 7.35−7.30 (m, 5H), 7.23 (d, $J$ = 7.6 Hz, 1H), 7.18 (d, $J$ = 7.4 Hz, 1H), 7.13 (d, $J$ = 8.4 Hz, 2H), 6.99 (d, $J$ = 3.9 Hz, 1H), 4.02 (s, 2H), 1.22 (s, 9H). $^{13}C$ NMR (100 MHz, $CDCl_3$) $\delta$ 148.8, 139.8, 135.0, 134.9, 134.6, 133.9 (d, $J$ = 107.2 Hz), 131.9, 131.8, 131.2, 128.4, 128.1, 128.0, 127.7, 126.2, 124.8, 124.6, 121.9, 121.8, 119.2, 119.0, 118.0, 116.8, 110.5, 34.3, 31.2, 29.5. $^{31}P$ NMR (162 MHz, $CDCl_3$) $\delta$ 21.34. HRMS (ESI) calcd for $C_{33}H_{30}NNaOP^+$ (M + $Na^+$) 510.1957, found: 510.1954.

*Diphenyl(1-(p-tolyl)-9H-pyrrolo[1,2-a]indol-2-yl)phosphine Oxide (**3l**).* Mp: 260.1−264.3 °C, light yellow solid (25.1 mg, 57%). $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 7.79−7.70 (m, 4H), 7.48 (d, $J$ = 8.1 Hz, 2H), 7.46−7.40 (m, 3H), 7.38−7.32 (m, 4H), 7.29 (d, $J$ = 7.5 Hz, 1H), 7.22 (d, $J$ = 7.6 Hz, 1H), 7.19−7.15 (m, 1H), 6.99−6.91 (m, 3H), 4.01 (s, 2H), 2.23 (s, 3H). $^{13}C$ NMR (100 MHz, $CDCl_3$) $\delta$ 139.8, 135.7, 135.2, 135.1, 134.6, 133.9 (d, $J$ = 107.1 Hz), 131.9, 131.8, 131.2, 131.2, 128.7, 128.6, 128.1, 128.0, 127.7, 126.2, 124.6, 121.9, 119.3, 119.1, 110.5, 29.6, 21.1. $^{31}P$ NMR (162 MHz, $CDCl_3$) $\delta$ 21.58. HRMS (ESI) calcd for $C_{30}H_{25}NOP^+$ (M + $H^+$) 446.1668, found: 446.1665.

*1-(4-(2-(Diphenylphosphoryl)-9H-pyrrolo[1,2-a]indol-1-yl)-phenyl)ethan-1-one (**3m**).* Mp: 263.8−267.6 °C, light yellow solid (21.1 mg, 45%). $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 7.79−7.72 (m, 8H), 7.48−7.43 (m, 3H), 7.39−7.34 (m, 4H), 7.31 (d, $J$ = 7.3 Hz, 1H), 7.25−7.18 (m, 2H), 6.91 (d, $J$ = 4.1 Hz, 1H), 4.06 (s, 2H), 2.51 (s, 3H). $^{13}C$ NMR (100 MHz, $CDCl_3$) $\delta$ 197.9, 139.4, 139.3, 136.6, 136.5, 134.5, 134.2, 133.3 (d, $J$ = 107.7 Hz), 132.6, 131.9, 131.8, 131.6, 131.6, 131.3, 130.8, 130.7, 129.0, 128.9, 128.5, 128.3, 128.2, 127.9, 126.3, 125.0, 120.9, 120.9, 120.2, 119.9, 118.0, 116.8, 110.7, 30.0, 26.6. $^{31}P$ NMR (162 MHz, $CDCl_3$) $\delta$ 21.61. HRMS (ESI) calcd for $C_{31}H_{25}NO_2P^+$ (M + $H^+$) 474.1617, found: 474.1622.

*(1-(4-Fluorophenyl)-9H-pyrrolo[1,2-a]indol-2-yl)diphenylphosphine Oxide (**3n**).* Mp: 265.5−267.9 °C, light yellow solid (22.7 mg, 51%). $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 7.79−7.69 (m, 4H), 7.62−7.55 (m, 2H), 7.48−7.41 (m, 3H), 7.38−7.33 (m, 4H), 7.30 (d, $J$ = 7.1 Hz, 1H), 7.23 (d, $J$ = 7.6 Hz, 1H), 7.20−7.16 (m, 1H), 6.93 (d, $J$ = 4.0 Hz, 1H), 6.84 (t, $J$ = 8.8 Hz, 2H), 3.99 (s, 2H). $^{13}C$ NMR (100 MHz, $CDCl_3$) $\delta$ 161.3 (d, $J$ = 243.7 Hz), 139.7, 135.3, 135.2, 134.4, 133.6 (d, $J$ = 107.2 Hz), 131.9, 131.8, 131.4, 131.4, 130.4, 130.3, 128.2, 128.1, 127.8, 126.2, 124.7, 121.0, 120.9, 119.3, 119.1, 118.1, 116.9, 115.0, 114.7, 110.6, 29.4. $^{19}F$ NMR (376 MHz, $CDCl_3$) $\delta$ −116.40. $^{31}P$ NMR (162 MHz, $CDCl_3$) $\delta$ 21.15. HRMS (ESI) calcd for $C_{29}H_{22}FNOP^+$ (M + $H^+$) 450.1418, found: 450.1416.

*(1-(4-(tert-Butyl)phenyl)-9H-pyrrolo[1,2-a]indol-2-yl)di-p-tolylphosphine Oxide (**3o**).* Mp: 105.5−106.8 °C, light yellow solid (24.0 mg, 47%). $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 7.64−7.58 (m, 4H), 7.46 (d, $J$ = 8.3 Hz, 2H), 7.42 (d, $J$ = 7.5 Hz, 1H), 7.31−7.27 (m, 1H), 7.22 (d, $J$ = 7.6 Hz, 1H), 7.17−7.10 (m, 7H), 6.97 (d, $J$ = 4.0 Hz, 1H), 4.01 (s, 2H), 2.32 (s, 6H), 1.23 (s, 9H). $^{13}C$ NMR (100 MHz, $CDCl_3$) $\delta$ 148.7, 141.3, 141.3, 139.8, 134.9, 134.8, 134.6, 131.9, 131.8, 131.5, 131.4, 130.9 (d, $J$ = 109.6 Hz), 128.8, 128.7, 128.4, 127.7, 126.2, 124.7, 124.5, 121.8, 121.7, 119.2, 119.0, 118.6, 117.4, 110.5, 34.3, 31.3, 29.5, 21.5. $^{31}P$ NMR (162 MHz, $CDCl_3$) $\delta$ 21.49. HRMS (ESI) calcd for $C_{35}H_{35}NOP^+$ (M + $H^+$) 516.2451, found: 516.2454.

*Di-p-tolyl(1-(p-tolyl)-9H-pyrrolo[1,2-a]indol-2-yl)phosphine Oxide (**3p**).* Mp: 94.3−96.0 °C, light yellow solid (23.0 mg, 49%). $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 7.64−7.57 (m, 4H), 7.50 (d, $J$ = 8.1 Hz, 2H), 7.43 (d, $J$ = 7.4 Hz, 1H), 7.29 (t, $J$ = 7.7 Hz, 1H), 7.22 (d, $J$ = 7.6 Hz, 1H), 7.18−7.13 (m, 5H), 6.97 (d, $J$ = 8.0 Hz, 2H), 6.92 (d, $J$ = 4.0 Hz, 1H), 4.00 (s, 2H), 2.35 (s, 6H), 2.24 (s, 3H). $^{13}C$ NMR (100 MHz, $CDCl_3$) $\delta$ 141.5, 139.8, 135.5, 135.2, 135.1, 134.6, 131.9, 131.8, 131.5, 130.9 (d, $J$ = 109.7 Hz), 128.9, 128.8, 128.7, 128.6, 127.6, 126.2, 124.5, 119.3, 119.1, 110.5, 29.6, 21.6, 21.1. $^{31}P$ NMR (162 MHz, $CDCl_3$) $\delta$ 21.68. HRMS (ESI) calcd for $C_{32}H_{28}NNaOP^+$ (M + $Na^+$) 496.1801, found: 496.1805.

*Diphenyl(1-(m-tolyl)-9H-pyrrolo[1,2-a]indol-2-yl)phosphine Oxide (**3q**).* Mp: 71.6−72.8 °C, light yellow solid (22.7 mg, 42%). $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 7.64−7.57 (m, 4H), 7.42 (d, $J$ = 8.3 Hz, 2H), 7.13 (t, $J$ = 8.7 Hz, 7H), 7.00 (s, 1H), 6.93 (d, $J$ = 3.5 Hz, 1H), 6.81 (d, $J$ = 6.9 Hz, 1H), 3.98 (s, 2H), 3.82 (s, 3H), 2.32 (s, 6H), 1.22 (s, 9H). $^{13}C$ NMR (100 MHz, $CDCl_3$) $\delta$ 157.2, 148.7, 141.3, 136.2, 133.8, 131.9, 131.8, 131.4, 130.9 (d, $J$ = 109.4 Hz), 128.8, 128.7, 128.4, 124.7, 119.0, 118.7, 112.6, 112.5, 110.8, 55.8, 31.2, 29.8, 21.5. $^{31}P$ NMR (162 MHz, $CDCl_3$) $\delta$ 21.39. HRMS (ESI) calcd for $C_{36}H_{37}NO_2P^+$ (M + $H^+$) 546.2556, found: 546.2550.

*(7-Methoxy-1-(p-tolyl)-9H-pyrrolo[1,2-a]indol-2-yl)di-p-tolylphosphine Oxide (**3r**).* Mp: 83.1−84.5 °C, light yellow solid (22.0 mg, 44%). $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 7.63−7.56 (m, 4H), 7.49 (d, $J$ = 8.1 Hz, 2H), 7.17−7.10 (m, 5H), 7.01−7.94 (m, 3H), 6.86 (d, $J$ = 4.0 Hz, 1H), 6.83−6.78 (m, 1H), 3.98 (s, 2H), 3.82 (s, 3H), 2.34 (s, 6H), 2.23 (s, 3H). $^{13}C$ NMR (100 MHz, $CDCl_3$) $\delta$ 157.2, 141.4, 136.2, 135.4, 134.9, 133.8, 131.9, 131.8, 131.6, 131.0 (d, $J$ = 109.7 Hz), 128.8, 128.7, 128.7, 128.5, 121.8, 119.1, 118.9, 112.6, 112.5, 110.8, 55.8, 29.9, 21.6, 21.1. $^{31}P$ NMR (162 MHz, $CDCl_3$) $\delta$ 22.02. HRMS (ESI) calcd for $C_{33}H_{31}NO_2P^+$ (M + $H^+$) 504.2087, found: 504.2083.

*Bis(4-bromophenyl)(1-phenyl-9H-pyrrolo[1,2-a]indol-2-yl)-phosphine Oxide (**3s**).* Mp: 238.2−239.7 °C, light yellow solid (25.3 mg, 43%). $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 7.60−7.55 (m, 6H), 7.50−7.44 (m, 5H), 7.33−7.27 (m, 2H), 7.18 (t, $J$ = 7.5 Hz, 3H), 7.09 (t, $J$ = 7.4 Hz, 1H), 6.97 (d, $J$ = 4.0 Hz, 1H), 4.02 (s, 2H). $^{13}C$ NMR (100 MHz, $CDCl_3$) $\delta$ 139.5, 135.7, 135.5, 134.5, 133.9, 133.4, 133.3, 132.5 (d, $J$ = 109.0 Hz), 131.5, 131.4, 128.7, 128.2, 127.8, 127.4, 126.7, 126.6, 126.5, 126.3, 124.9, 122.0, 121.9, 119.3, 119.1, 116.9, 115.7, 110.7, 29.5. $^{31}P$ NMR (162 MHz, $CDCl_3$) $\delta$ 19.88. $C_{29}H_{21}Br_2NOP^+$ (M + $H^+$) 587.9722, f ound: 587.9721.

*Bis(4-methoxyphenyl)(1-phenyl-9H-pyrrolo[1,2-a]indol-2-yl)-phosphine Oxide (**3t**).* Mp: 183.4−185.2 °C, light yellow solid (22.3 mg, 46%). $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 7.67 (s, 1H), 7.65−7.61 (m, 5H), 7.42 (d, $J$ = 7.4 Hz, 1H), 7.30 (t, $J$ = 7.6 Hz, 1H), 7.23 (d, $J$ = 7.6 Hz, 1H), 7.19−7.14 (m, 3H), 7.05 (t, $J$ = 7.4 Hz, 1H), 6.94 (d, $J$ = 4.1 Hz, 1H), 6.85 (dd, $J$ = 8.8, 2.2 Hz, 4H), 4.01 (s, 2H), 3.79 (s, 6H). $^{13}C$



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NMR (100 MHz, $CDCl_3$) $\delta$ 161.9, 161.9, 139.8, 135.4, 135.3, 134.5, 134.4, 133.7, 133.5, 131.8, 129.5, 128.7, 128.6, 128.0, 127.8(d, $J$ = 104.0 Hz), 127.7, 126.2, 126.0, 125.9, 125.0, 124.5, 121.8, 121.7, 119.4, 119.1, 118.9, 117.7, 113.7, 113.6, 110.5, 55.3, 29.7. $^{31}P$ NMR (162 MHz, $CDCl_3$) $\delta$ 21.11. $C_{31}H_{26}NNaO_3P^+$ (M + $Na^+$) 514.1543, found: 514.1546.

*Bis(4-methoxyphenyl)(1-(thiophen-2-yl)-9H-pyrrolo[1,2-a]indol-2-yl)phosphine Oxide (**3u**).* Mp: 213.7−214.9 °C, light yellow solid (18.6 mg, 38%). $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 7.67−7.61 (m, 6H), 7.43 (d, $J$ = 7.4 Hz, 1H), 7.30 (s, 1H), 7.23 (d, $J$ = 7.6 Hz, 1H), 7.17 (t, $J$ = 3.6 Hz, 2H), 7.06 (t, $J$ = 7.4 Hz, 1H), 6.94 (d, $J$ = 4.1 Hz, 1H), 6.85 (dd, $J$ = 8.8, 2.1 Hz, 4H), 4.02 (s, 2H), 3.80 (s, 6H). $^{13}C$ NMR (100 MHz, $CDCl_3$) $\delta$ 161.88, 161.85, 139.77, 135.40, 135.30, 134.48, 134.37, 133.64, 133.53, 131.81, 129.48, 128.71, 128.59, 128.27, 128.00, 127.86, 127.68, 127.23, 126.4 (d, $J$ = 106.3 Hz), 126.15, 126.03, 125.01, 124.91, 124.53, 121.78, 121.70, 119.34, 119.13, 118.86, 117.68, 113.67, 113.54, 110.48, 77.37, 77.05, 76.74, 55.25, 29.64. $^{31}P$ NMR (162 MHz, $CDCl_3$) $\delta$ 21.83. $C_{29}H_{25}NO_3PS^+$ (M + $H^+$) 498.1287, found: 498.1289.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b02673.

$^1H$, $^{31}P$, $^{19}F$, and $^{13}C$ NMR spectra of compounds **3a−3u** (PDF)

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### Notes

The authors declare no competing financial interest.

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