Addition Reactions of a Phosphorus Triamide to Nitrosoarenes and Acylpyridines

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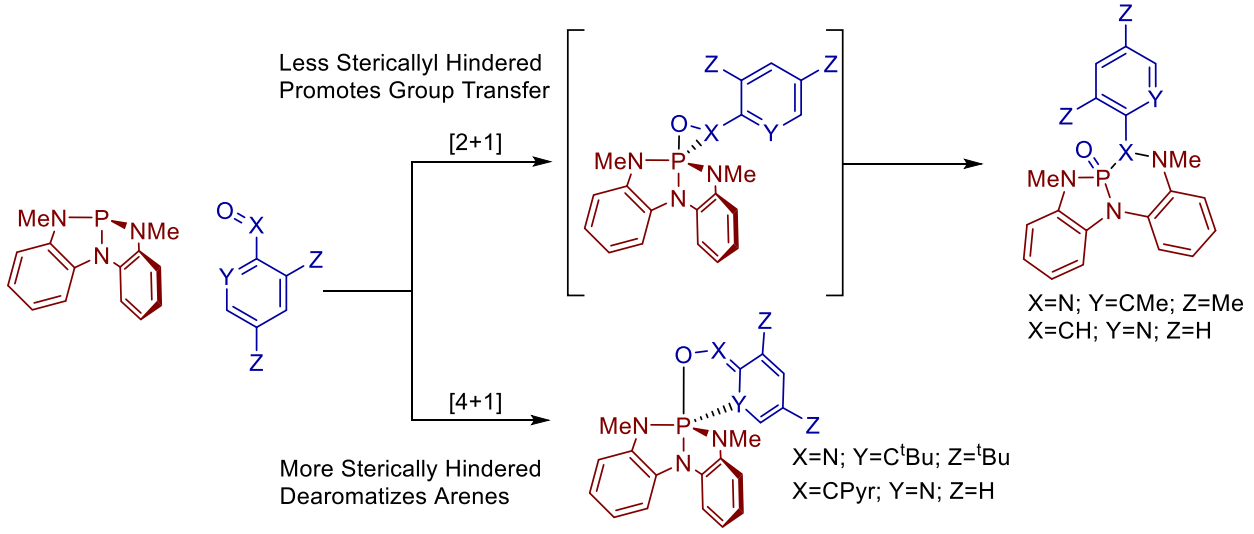
ABSTRACT *Tricoordinate phosphorus compounds react with a wide variety of double bonds through addition reactions. The dipolar and cyclic products formed are important intermediates in organophosphorus chemistry. We investigated the reactivity between phosphorus triamide* ***1*** *and nitrosoarenes and 2-acylpyridines. For sterically congested substrates, the formation of* σ^5, λ^5*-phosphorus products is observed. DFT calculations indicate this product is formed through a concerted [4+1] mechanism. For less sterically congested substrates, products are observed arising from cleavage of the N=O or C=O bond with formation of a terminal P=O bond and aryl nitrene or carbene migration into a P–N bond of the phosphorus triamide core. DFT calculations are consistent with an initial [2+1] addition to phosphorus followed by formal carbene/nitrene migration in these cases.*

GRAPHICAL ABSTRACT

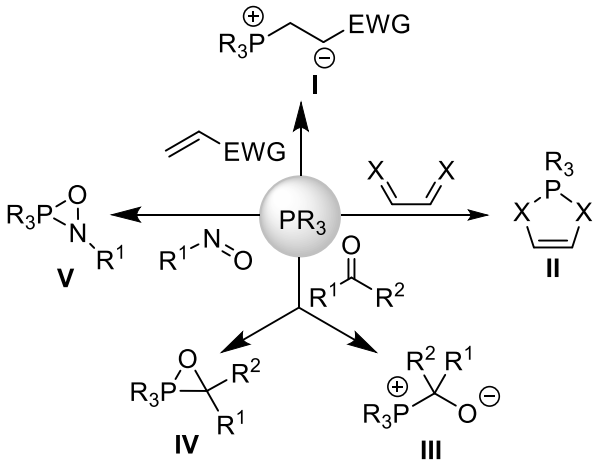


KEYWORDS Phosphorus; Addition Reaction; Nitrosoarene; Acylpyridine; DFT Calculations

INTRODUCTION

Tricoordinate phosphorus compounds are known to undergo a number of addition reactions with unsaturated organic substrates.[1–3] For instance, polarized alkenes undergo conjugate addition to give dipolar intermediates **I**, which are key intermediates in numerous organophosphorus-mediated and -catalyzed transformations.[4–14] For certain α,β-unsaturated carbonyl compounds, the intermediate phosphonium enolate can

undergo a ring closing to give persistent cyclic σ^5, λ^5-phosphoranes **II** through a stepwise, formal [4+1] addition. The synthetic utility of these intermediates has been demonstrated.[15, 16]



Scheme 1. Phosphorus adducts formed with various unsaturated compounds.

Related addition chemistry of tricoordinate phosphorus compounds is known for heteroalkene substrates, such as carbonyl (C=O) and nitroso (N=O) compounds. The addition of tricoordinate phosphines to simple carbonyl compounds is known to lead to a diversity of adducts with 1:1 stoichiometry, including zwitterionic phosphonium alkoxides **III** and oxaphosphirane [2+1] adducts **IV**.[17–22] Similarly, oxazaphosphiranes **V** have been suggested to arise from [2+1] addition of phosphines to nitrosoarenes. σ^5, λ^5 Dioxophospholenes with 1-to-1 stoichiometry are formed via formal [4+1] addition to 1,2-dicarbonyl compounds.[23, 24] The synthetic importance of these intermediates are underscored by the numerous reports in which the addition of phosphine to carbonyl or nitroso substrates leads to net deoxygenation with transfer of a carbene or nitrene equivalent, respectively.[19, 25–27]

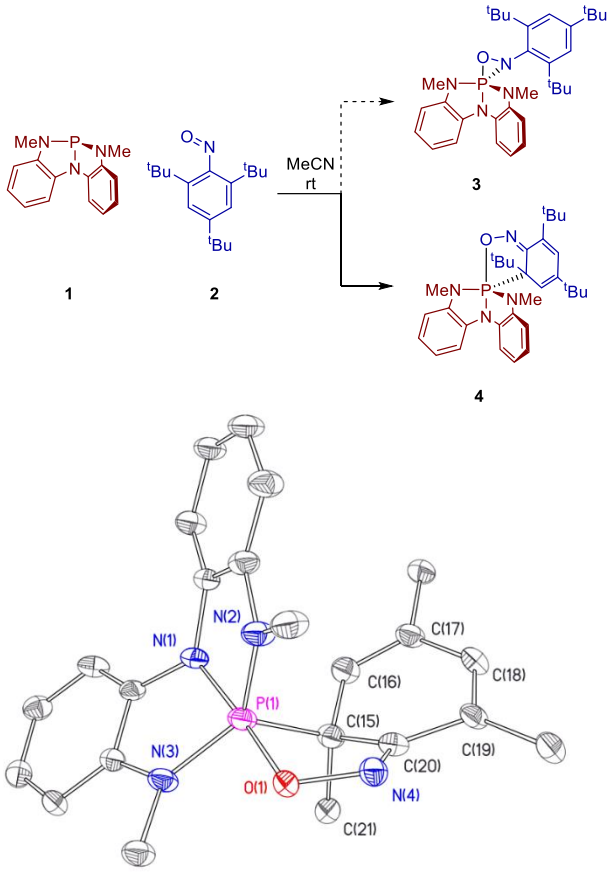
We have recently been investigating the reactivity of bicyclic phosphorus triamide **1**.[28–30] Compound **1** and related species have been shown to undergo a number of addition reactions with polarized single bonds (O-H, N-H, B-H).[31–33] In order to probe the reactivity of **1** with respect to a selected number of polar unsaturated substrates, we report here the addition of **1** to nitrosoarenes and acylpyridines. We find evidence for a partitioning of the reaction pathway along [2+1] and [4+1] addition modes as a function of the steric demand of the electrophilic substrate.

RESULTS AND DISCUSSION

The reaction of **1** (^{31}P NMR δ 160 ppm) with 2,4,6-tri-*tert*-butylnitrosobenzene (**2**) in acetonitrile resulted in the consumption of the starting materials and deposition of a yellow precipitate. When redissolved in benzene, a ^{31}P NMR spectrum of the precipitate shows a single peak whose chemical shift (δ -19 ppm) suggests a

pentacoordinate phosphorus environment.[28, 34, 35] By ^{1}H NMR spectroscopy, both the *N*-methyl groups of the triamide ligand as well as the *tert*-butyl groups of the nitroso fragment are found to be inequivalent. Both the ^{31}P and ^{13}C NMR spectrum provide evidence for coupling between phosphorus and an ortho carbon atom of the nitrosoarene fragment with a magnitude ($^{1}J_{C-P}$ = 154 Hz) indicative of a direct bonding interaction and is not consistent with the previously expected oxazaphosphirane (**3**).[36]

The same reaction between **1** and **2** in a standing solution of acetonitrile at room temperature deposits large diffraction-quality crystals overnight. Refinement of the X-ray diffraction data provides a model describing oximinophospholene **4** (Scheme 2), in which the nitrosoarene has added in 1,4-fashion to give a σ^{5},λ^{5}-phosphorus product. The bond distance between the nitroso nitrogen and ipso carbon (N_4–C_{20}) bond has shortened to 1.29(3) Å, approaching that of a double bond (typically 1.28 Å).[37] Conversely, the nitroso N–O bond distance is elongated (N_4–O_1 = 1.42(4) Å) as expected for a single bond order. The formation of the new P–C bond in



Scheme 2. Top) Reactivity of phosphorus triamide 1 with 2,4,6-tri-tert-butylnitrosobenzene Bottom) Crystal structure of 4 indicating the dearomatization of the aryl ring Thermal ellipsoids rendered at 50% probability level. Tert-butyl methyls and C–H hydrogen atoms excluded for clarity. Selected bond lengths (Å) and angles (°) of P–O(1) 1.72(1), P–C(15) 1.89(9), O(1)–N(4) 1.42(4), N(4)–C(20) 1.29(3), C(19)–C(20) 1.47(7), C(18)–C(19) 1.34(2), C(17)–C(18) 1.46(4), C(17)–C(16) 1.34(6), O(1)-P(1)-N(4) 110.8(7), O(1)-P(1)-C(15) 86.4(2), C(21)-C(15)-P(1) 115.2(2).

4 (P_1–C_{15} = 1.89(9) Å, the average P–C bond is 1.85 Å), coincides with the breaking of the aromaticity of the nitrosoarene; the C–C bonds of the former aryl ring show alternating bond lengths between C_{16} through C_{20}.[37]

The preference for the [4+1] adduct **4** over the [2+1] adduct **3** is supported by DFT calculations. At the M06-2X /6-311+G(d,p) level of theory, compound **4** is predicted to be more stable than **3** with an energy difference of 14.2 kcal/mol, in accord with the experimental observation. Interestingly, an opposite thermochemical outcome is predicted if parent nitrosobenzene (i.e. devoid of 2,4,6-tri-*tert*-butyl substituents) is employed in the calculation (at the M06-2X /6-311++G(2d,2p) level of theory). As depicted in Figure 1, the [2+1] adduct **3'** is favored over the [4+1] adduct **4'** by 9.3 kcal/mol. A further survey of the energy landscape suggests that a stepwise pathway for the formation of **3'** ($\Delta G^{\ddagger}$ = 22.4 kcal/mol via **TS1**) is favored over a direct [2+1] cycloaddition ($\Delta G^{\ddagger}$ = 32.6 kcal/mol via **TS3**), whereas a concerted [4+1] pathway resides at lower energy ($\Delta G^{\ddagger}$ = +23.6 kcal/mol via **TS6**) relative to a stepwise formation of **4'** ($\Delta G^{\ddagger}$ = 26.4 kcal/mol via **TS4**).

The major hypothesis emerging from the DFT studies is that steric effects might dictate the [2+1] vs. [4+1] partitioning of reactions involving **1** and substituted nitrosobenzenes. Consistent with the forgoing prediction, when **1** is treated with the less sterically hindered 2,4,6-trimethylnitrosobenzene (**5**) (Scheme 3), an oximinophosphole analogous to **4** is not formed. Rather a single species (**6**) with a ^{31}P

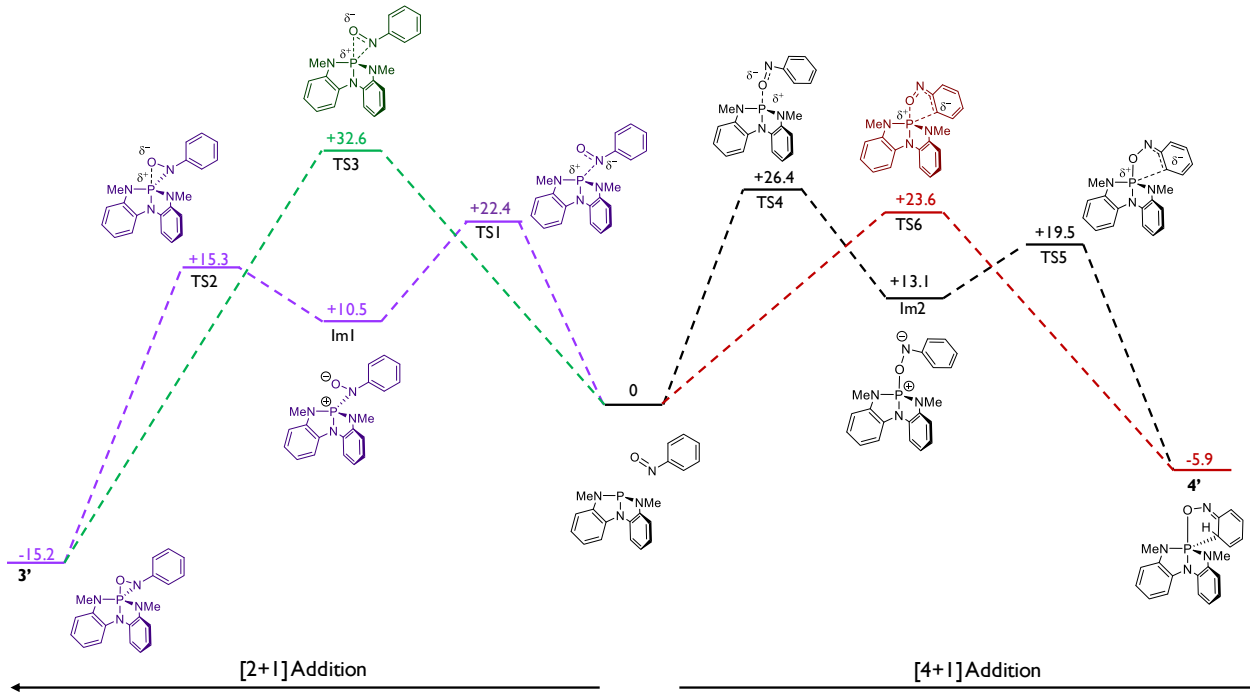
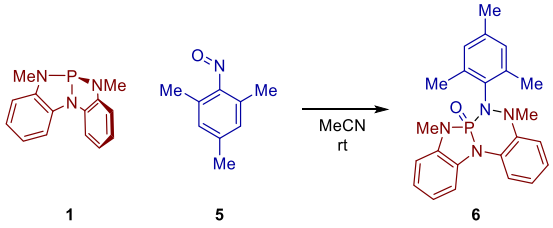
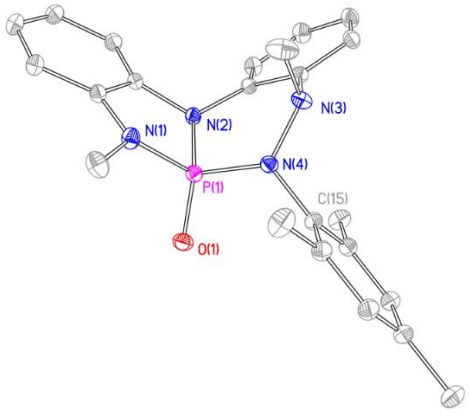


Figure 1. DFT calculations on formation of oxazaphosphirane 3' and oximinophosphole 4' using Gaussian 09 M06-2X /6-311++G(2d,2p).

NMR shift of δ +18 ppm is produced. Five distinct peaks in the ^{1}H NMR spectrum corresponding to the methyl groups (δ 2.90, 2.46, 2.38, 2.09, and 2.01 ppm) indicate a low-symmetry structure with respect to both the phosphorus triamide core as well as the mesityl moiety.

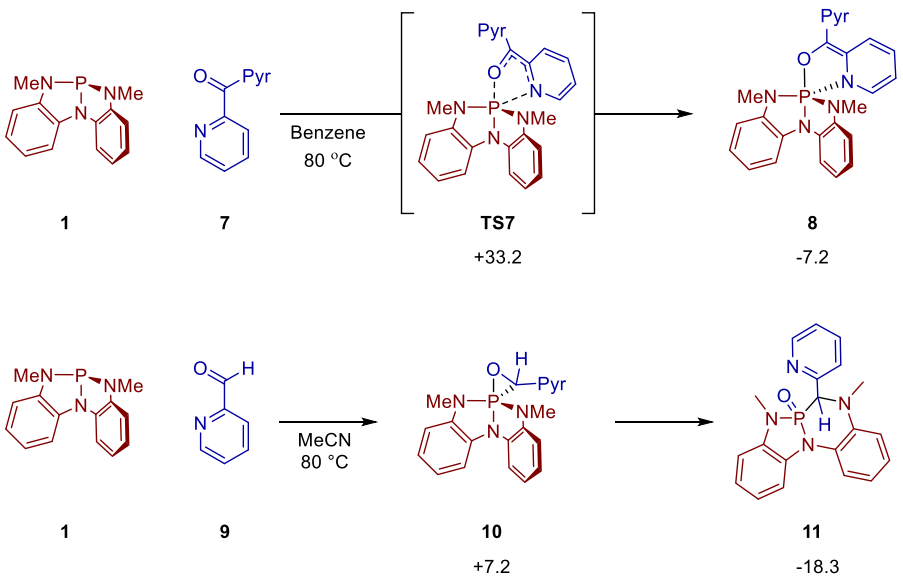
X-ray diffraction data from a single crystalline sample of **6**, prepared from acetonitrile and dichloromethane by slow evaporation, coincides with the spectral observations and indicates a structure as depicted in Scheme 3. In effect, compound **6** represents a formal migration of the mesityl nitrene into a P-N bond of the phosphorus triamide core with the formation of a terminal P=O bond (Scheme 3).





Scheme 3. Top) Product of 1 with 2,4,6-trimethylnitrosobenzene upon nitrenoid migration. Bottom) Crystal structure of 6 displaying different surroundings for all methyl groups. Thermal ellipsoids rendered at 50% probability level. C–H hydrogen atoms excluded for clarity. Selected bond lengths (Å) and angles (°) of P–O(1) 1.47(0), P(1)–N(1) 1.67(2), P(1)–N(2) 1.68(3), P(1)–N(4) 1.65(0), N(3)–N(4) 1.43(1), N(4)–C(15) 1.44(3), O(1)-P(1)-N(1) 114.0(9), O(1)-P(1)-N(2) 121.0(9), O(1)-P(1)-N(4) 110.4(4), N(1)-P(1)-N(4) 114.6(7), P(1)-N(4)-C(15) 122.6(1), N(3)-N(4)-C(15) 114.9(4).

On the basis of prior literature which supports the formation of nitrene or nitrenoid reactive intermediates by deoxygenation of nitro- and nitrosoarenes, [26, 38–40] we infer that compound **6** is formed via initial access to an oxazaphosphirane compound, similar to **3**, followed by subsequent arylnitrene migration. Indeed, the relative Gibbs free energies computed by DFT support this hypothesis; the Gibbs free energy of **6** is 31.8



Scheme 4. (Top) [4+1] addition of 1 with 2,2′-bispyridylketone results in oximinophospholene 8. (Bottom) Formation of 11 via treating 1 with 2-pyridinecarboxaldehyde 9. DFT calculations using Gaussian 09 M06-2X /6-311++G(2d,2p).

kcal/mol lower than that of the corresponding oxazaphosphirane.

A related [4+1] vs. [2+1] dichotomy is observed in addition reaction of **1** with 2-acylpyridines. Treatment of **1** with bis(2-pyridyl) ketone **7** at 80 °C in benzene results in formation of a deep red solid. Dissolution in benzene and analysis by ^{1}H NMR spectroscopy reveals the presence of new signals appearing at intermediate chemical shift (ca. δ 5.77 ppm and 4.82 ppm). A ^{31}P NMR spectrum shows a single septet at δ -50 ppm. Based on these observations and by analogy with **3**, the structure is postulated to be that of **8**. [41] Computations support **8** as being thermodynamically downhill by 7.2 kcal/mol via concerted [4+1] addition analogous to the formation of **4** (Scheme 4).

By contrast, reaction of **1** with 2-pyridinecarboxaldehyde (**9**) for two hours at 80 °C resulted in the formation of a single product exhibiting an apparent multiplet (δ +32 ppm) in the ^{31}P NMR spectrum. A phosphorus-coupled doublet is observed in the ^{13}C NMR spectrum at δ 72.4 ppm with $^{1}J_{P-C}$=119 Hz coupling constant. Using ^{1}H NMR spectroscopy, a doublet integrating to one proton can be found at δ 5.35 ppm with a coupling constant J=22 Hz whose magnitude is consistent with two-bond $^{2}J_{P-H}$ spin-spin coupling. Moreover, two distinct methyl groups can be found at δ 2.80 ppm ($^{3}J_{P-H}$=8.9 Hz) and δ 2.0 ppm ($^{4}J_{P-H}$=2.1 Hz), indicating the triamide ligand that is no longer symmetrically bound to the phosphorus.

Taken together, these spectral data are consistent with the assignment of the reaction product as **11** (Scheme 4), in which aldehyde deoxygenation by phosphorus triamide **1** leads to carbene migration into one of the distal P-N bonds and formation of a terminal P=O. As was suggested for **6**, the formation of **11** presumably arises via an unobserved [2+1] adduct, ground state energies by DFT deem this feasible as well. Indeed, the formation of carbene and carbenoid reactive equivalents by P(III) mediated carbonyl deoxygenation is extensively supported in the literature.[2, 23, 24, 42–44]

CONCLUSIONS

In this article, we show that phosphorus triamide **1** reacts with 2,4,6-tri-*tert*-butylnitrosobenzene and bis(2-pyridyl) ketone to form a σ^5,λ^5-phosphole. Crystallography data confirms the loss of aromaticity in the arene ring while DFT calculations indicate these reactions to proceed through a concerted [4+1] cycloaddition. In contrast, when either 2,4,6-trimethylnitrosobenzene or 2-pyridine carboxaldehyde is treated with **1** a deoxygenative process occurs in which the substrate inserts into the phosphorus triamide core. We believe this ring expansion to proceed through [2+1] cycloaddition followed by formal nitrene and carbene migrations. The compounds described in this work provide insight into the diverging reactivity of important intermediates in organophosphorus transformations.

ACKNOWLEDGEMENTS

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EXPERIMENTAL SECTION

General information. Phosphorus triamide **1** was prepared according to literature procedures.[45] All other reagents were purchased from commercial vendors and used without further purification unless otherwise indicated. Manipulations conducted under an inert atmosphere (N_2) are noted accordingly in the following procedures. ^{1}H, ^{13}C and ^{31}P NMR spectra were collected with either Bruker AVANCE-400 or AVANCE Neo-500 spectrometers and processed using MestReNova. ^{1}H NMR

chemical shifts are given in ppm with respect to the solvent residual peak ($CDCl_3$, δ 7.26 ppm; C_6D_6 δ7.16 ppm). $^{13}C\{^1H\}$ NMR chemical shifts are given in ppm with respect to the solvent ($CDCl_3$ δ 77.16 ppm, C_6D_6 δ 128.06 ppm). ^{31}P NMR chemical shifts are given in ppm with respect to 85% H_3PO_4 (δ 0.0 ppm) as an external standard. Multiplicities are described as s = singlet, br s = broad singlet, d = doublet, t = triplet, q = quartet, dd = doublet of doublets, td = triplet of doublets, m = multiplet. Coupling constants are reported in Hertz (Hz). High-resolution ESI mass spectra were obtained at the MIT department of chemistry instrumentation facility on an Agilent 6545 QTOF/Agilent 1260 LC system.

2,4,6-Tri-*tert*-butylnitrosobenzene (**2**).[46] At 0°C, *m*-chloroperbenzoic acid (3.9 g, 2.0 equiv) in diethyl ether (25 mL) was added to 2,4,6-*tert*-butylaniline (3.0 g, 1.0 equiv) in diethyl ether (10 mL) and stirred overnight. The bright green solution was then treated with saturated sodium bicarbonate solution (5.0 mL) and the biphasic mixture was transferred to a separatory funnel and partitioned. The organic phase was washed with water, dried over Na_2SO_4 and filtered through a plug of silica gel. The filtrate was then concentrated to yield **2** as a bright green solid (1.7 g) in 52% yield. ^1H NMR (400 MHz, benzene-d_6) δ 7.43 (s, 2H), 1.22 (s, 18H), 1.21 (s, 9H).

2,4,6-Trimethylnitrosobenzene (**5**).[46] At 0°C, *m*-chloroperbenzoic acid (17 g, 2.0 equiv) in diethyl ether (50 mL) was added to 2,4,6-trimethylaniline (5.2 mL, 1.0 equiv) in diethyl ether (50 mL) and stirred overnight. During the addition, the brown solution first turned green and then became a brown suspension with white precipitate. The reaction mixture was treated with saturated sodium bicarbonate solution (5.0 mL) and the biphasic mixture was transferred to a separatory funnel and partitioned. The aqueous layer was extracted twice with diethyl ether. The combined organic layers were concentrated to yield an orange/brown solid, which was purified by silica gel chromatography (2/1 → 1/1 hexane/CH_2Cl_2). Product **5** eluted as a green band on the silica gel column, yielding an orange/white solid upon collection and concentration (1.6 g, 11 mmol, 29%). ^1H NMR ($CDCl_3$) δ 6.99 (s, 2H), 2.62 (s, 2H), 2.41 (s, 4H), 2.34 (s, 1H), 2.33 (s, 2H).

Adduct **4.** In a glovebox, compound **1** (50 mg, 0.20 mmol) was dissolved in acetonitrile (2.0 mL). 2,4,6-Tri-*tert*-butylnitrosobenzene

(30 mg, 0.20 mmol) was added and the resultant mixture was aged overnight at ambient temperature, during which time yellow crystals of adduct **4** developed and were collected by filtration (17 mg, 21% yield). ^{1}H NMR (500 MHz, benzene-d_6) δ 7.36 (dd, J = 7.5, 1.5 Hz, 1H), 7.31 – 7.28 (m, 1H), 6.97 (tt, J = 7.6, 1.4 Hz, 1H), 6.93 (td, J = 7.6, 1.6 Hz, 1H), 6.84 – 6.80 (m, 2H), 6.59 (dt, J = 7.5, 1.4 Hz, 1H), 6.32 – 6.25 (m, 1H), 6.07 (t, J = 1.6 Hz, 1H), 5.84 (dd, J = 9.5, 1.7 Hz, 1H), 3.43 (d, J = 7.1 Hz, 3H), 2.96 (d, J = 9.1 Hz, 3H), 1.45 (s, 9H), 0.84 (s, 9H), 0.79 (s, 9H). ^{13}C NMR (126 MHz, benzene-d_6) δ 165.95 (d, J = 10.3 Hz), 144.13 (d, J = 14.5 Hz), 141.71 (d, J = 11.4 Hz), 139.26 (d, J = 15.6 Hz), 136.18 (d, J = 7.3 Hz), 135.53 (d, J = 10.0 Hz), 134.26 (d, J = 18.8 Hz), 124.16 (d, J = 5.7 Hz), 121.32, 120.57, 120.20, 120.14, 118.95, 112.53 (d, J = 7.8 Hz), 110.76 (d, J = 7.2 Hz), 109.91 (d, J = 10.7 Hz), 108.97 (d, J = 9.6 Hz), 59.45 (d, J = 154.8 Hz), 39.88, 36.21, 35.17, 34.19, 33.11 (d, J = 2.9 Hz), 29.93, 28.59 (d, J = 1.9 Hz), 26.32 (d, J = 6.1 Hz). ^{31}P NMR (203 MHz, benzene-d_6) δ -19.61 (dt, J = 16.9, 7.9 Hz). HRMS (EI) calcd for Chemical Formula: $\{C_{32}H_{43}N_4O_3P\}^+$, 531.3247; found, 531.3244.

Adduct **6.** In a glovebox, a vial was charged with compound **1** (100 mg, 0.39 mmol) and 2-nitrosomesitylene (58 mg, 0.39 mmol). The solids were then dissolved in benzene (3.0 mL) and heated to reflux for 2h. The solution was then concentrated and product **6** was isolated without further purification. ^{1}H NMR (400 MHz, benzene-d_6) δ 7.26 (dd, J = 7.6, 1.6 Hz, 1H), 6.91 (tt, J = 7.7, 1.2 Hz, 2H), 6.88 – 6.79 (m, 3H), 6.75 – 6.66 (m, 3H), 6.47 (dt, J = 7.7, 1.1 Hz, 1H), 2.91 (d, J = 8.9 Hz, 3H), 2.47 (d, J = 1.4 Hz, 3H), 2.40 (s, 3H), 2.10 (s, 3H), 2.02 (s, 3H). ^{13}C NMR (101 MHz, benzene-d_6) δ 151.15 (d, J = 3.0 Hz), 140.17, 138.33 (d, J = 13.7 Hz), 137.39, 137.17, 136.29 (d, J = 16.0 Hz), 134.65 (d, J = 4.3 Hz), 134.61 (d, J = 16.7 Hz), 130.94, 129.19, 128.67 (d, J = 4.4 Hz), 127.09, 125.56, 122.52, 122.17, 119.74, 111.07 (d, J = 8.1 Hz), 108.67 (d, J = 9.3 Hz), 43.36, 29.23 (d, J = 4.5 Hz), 20.93, 20.43, 19.43. ^{31}P NMR (162 MHz, C_6D_6) δ 18.30. HRMS (EI) calcd for Chemical Formula: $\{C_{23}H_{26}N_4OP\}^+$, 405.1839; found, 405.1838.

Adduct **8.** In a glovebox, a vial charged with a solution of compound **1** (100 mg, 0.39 mmol) in benzene (2.0 mL) was treated with bis(2-pyridyl)ketone (41 mg, 0.39 mmol). The mixture was then heated to reflux for 2 h, at which time the reaction was judged

complete by ^{31}P NMR spectroscopy. Removal of solvent in vacuo gave **8** as a dark red glass in quantitative yield. ^{1}H NMR (500 MHz, benzene-d_6) δ 8.53 – 8.47 (m, 1H), 8.23 (ddt, J = 9.6, 2.7, 1.3 Hz, 1H), 7.37 – 7.32 (m, 3H), 7.27 (td, J = 7.7, 1.9 Hz, 1H), 6.99 (ddd, J = 8.7, 7.2, 2.2 Hz, 1H), 6.96 – 6.91 (m, 4H), 6.82 – 6.77 (m, 1H), 6.52 (ddd, J = 7.4, 4.8, 1.2 Hz, 1H), 6.46 (dt, J = 7.4, 1.6 Hz, 2H), 5.77 (dd, J = 9.6, 5.8 Hz, 1H), 4.82 (dddd, J = 7.4, 5.6, 4.2, 1.3 Hz, 1H), 3.00 (d, J = 10.1 Hz, 6H). ^{31}P NMR (203 MHz, benzene-d_6) δ -48.29. ^{13}C NMR (126 MHz, benzene-d_6) δ 149.42, 135.63, 134.39, 134.23, 132.40 (d, J = 4.4 Hz), 132.30, 128.22, 127.98, 126.44, 125.23 (d, J = 10.4 Hz), 121.64, 120.21 (d, J = 7.0 Hz), 119.67, 116.97, 115.15, 111.53 (d, J = 9.1 Hz), 109.76 (d, J = 11.8 Hz), 105.72 (d, J = 7.8 Hz), 33.47. MS (ESI) calcd for Chemical Formula: $\{C_{39}H_{48}N_3O_3P\}$+, 637.3; found, 637.3.

Adduct **11.** In a glovebox, a vial was charged with compound **1** (30 mg, 0.12 mmol) and pyridine-2-carboxaldehyde (13 mg, 0.12 mmol). The solids were then dissolved in benzene (3.0 mL) and heated to reflux for 2h. The solution was then concentrated and product **11** was isolated in quantitative yield. ^{1}H NMR (500 MHz, benzene-d_6) δ 8.39 (d, J = 4.7 Hz, 1H), 7.27 (dd, J = 7.6, 1.6 Hz, 1H), 7.03 (td, J = 8.0, 1.6 Hz, 1H), 6.99 (ddt, J = 8.2, 2.0, 1.1 Hz, 1H), 6.92 (dd, J = 7.6, 1.7 Hz, 1H), 6.86 (d, J = 7.7 Hz, 1H), 6.81 (qt, J = 8.0, 7.5, 1.1 Hz, 2H), 6.68 (t, J = 7.8 Hz, 1H), 6.60 – 6.53 (m, 1H), 6.53 (dd, J = 8.0, 1.4 Hz, 1H), 6.34 (d, J = 7.7 Hz, 1H), 5.35 (dthept, J = 22.0, 7.8, 1.0 Hz, 1H), 2.80 (d, J = 8.9 Hz, 3H), 2.30 (d, J = 2.1 Hz, 3H). ^{13}C NMR (126 MHz, benzene-d_6) δ 156.65 (d, J = 3.3 Hz), 148.86, 144.55 (d, J = 3.8 Hz), 136.86 (d, J = 11.7 Hz), 135.78, 134.39 (d, J = 13.0 Hz), 128.64 (d, J = 4.6 Hz), 128.22, 127.65, 122.39 (d, J = 2.3 Hz), 122.15, 121.41, 120.61, 119.69, 116.85, 109.40 (d, J = 6.3 Hz), 107.87 (d, J = 7.8 Hz), 72.44 (d, J = 119.3 Hz), 39.08 (d, J = 12.9 Hz), 26.79 (d, J = 4.8 Hz). ^{31}P NMR (162 MHz, C_6D_6) δ 31.95. HRMS (EI) calcd for Chemical Formula: $\{C_{20}H_{20}N_4OP\}^+$, 363.1369; found, 363.1365.

The Supplemental Materials are available online.

Crystallographic data for compounds **4** and **6** has been deposited at the Cambridge Crystallographic Data Center (CCDC numbers 1993347 and CCDC 1993348). Copies of the information may be obtained free of charge from The Director, CCDC, 12 Union Road, Cambridge CB2 1 EZ, UK (Fax:

+ 44-1223-336033; email: deposit@ccdc.cam.ac.uk or www.ccdc.cam.ac.uk).

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