DOI: 10.1002/ejoc.201400120

Synthesis and Selected Reactivity Studies of a Dissymmetric (Phosphinoylmethylpyridine *N*-Oxide) Methylamine Platform

Sabrina Ouizem,[a] Sylvie L. Pailloux,[a] Alisha D. Ray,[a] Eileen N. Duesler,[a] Diane A. Dickie,[a] Robert T. Paine,*[a] and Benjamin P. Hay[b]

Keywords: N ligands / Chelates / Ligand design / Lanthanides / Nitrogen oxides

Efficient syntheses for the precursor molecules, 2-{6-[((diphenylphosphoryl)methyl)pyridin-2-yl]methyl}isoindoline-1,3-dione (**2**), 2-[(1,3-dioxoisoindolin-2-yl)methyl]-6-[(diphenylphosphoryl)methyl]pyridine 1-oxide (**3**), and their 6-[bis(2-(trifluoromethyl)phenyl)phosphoryl]methyl analogues are reported along with their transformations into the dissymmetric ligands, [(6-(aminomethyl)pyridin-2-yl)methyl]diphenylphosphine oxide (**4**), 2-(aminomethyl)-6-[(diphenylphosphoryl)methyl]pyridine 1-oxide (**5**) and 2-(aminomethyl)-6-{[bis(2-(trifluoromethyl)phenyl)phosphoryl]methyl}pyridine 1-oxide (**5-F**). Selected reactivity of the aminomethyl substituent of **4** and **5**, as well as complexation reactions of several of the compounds with lanthanide(III) ions are described. Molecular structures of three uniquely different complexes, {Pr{2-[HC(O)N(H)CH_2]-6-[$Ph_2P(O)CH_2$]-C_5H_3NO}$(NO_3)_3(MeOH)$}$_2$, {Eu{2-[$(Me_2N)_2CN(H^+)CH_2$]-6-[$Ph_2P(O)CH_2$]$C_5H_3N(H)^+$}$(NO_3)_4(OMe)$} and {Er{2-[$(C_8H_4O_2)$-NCH_2]-6-[$Ph_2P(O)CH_2$]$C_5H_3N(O)$}$(NO_3)_3(MeOH)$}·$(CH_3)_2$-CO, have been determined by single-crystal X-ray diffraction methods. The observed and computationally modeled structures that employ bidentate and tridentate ligand/metal interactions are compared. These results suggest further ligand modifications that should provide improved solvent extraction reagents.

Introduction

Organic chelating ligands have been employed for many years as critical enabling components in metal ion analytical detection schemes and solvent extraction-based separation processes. In particular, there has been much interest given to the development of robust chelating ligands for the separation of chemically similar f-block ions present in highly acidic aqueous nuclear process solutions.[1] In addition, renewed interest in the reclamation of rare-earth ions from low-grade ores and recycle materials[2] has also stimulated parallel growth in the design and synthesis of selective chelating ligands for this application. As part of efforts to more fully describe factors that control ligand chelate interactions on f-block element ions, we have previously described syntheses for multidonor site molecules based upon pyridine and pyridine *N*-oxide platforms decorated with phosphine oxide[3] and amide[4] functional groups. In the former class of compounds, this included representatives illustrated by **A**–**E** (Figure 1). Examples of **A** and **C** were found to produce strong bidentate O_NO_P binding conditions with lanthanide (Ln) ions, whereas **E** was observed to form tridentate $O_NO_PO_P$ interactions. Unexpectedly, in the presence of two or more equivalents of ligand, these neutral molecules were observed to partially or totally displace charge-compensating anions, for example nitrate, from the inner coordination sphere of the Ln^{III} cations. Examination of the solvent extraction behavior of these compounds revealed that examples of **C** and **E** display particularly favorable performance including increasing extraction efficiency with increasing nitric acid concentration up to ca. 1 M.[5] This led to interest in possible applications for these ligands in advanced separation schemes wherein the ligands would be incorporated into an ionic liquid solvent or onto a solid support. However, before such systems can be developed and evaluated, it is necessary to explore reaction chemistry for the platforms that will facilitate these efforts.

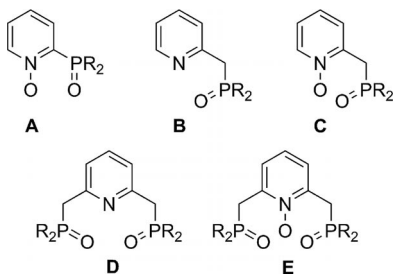


Figure 1. Generalized structures for ligand types **A**–**E**.

[a] Department of Chemistry and Chemical Biology, University of New Mexico,
Albuquerque, NM 87131, USA
E-mail: rtpaine@unm.edu
www.unm.edu/~rtpaine/
[b] Chemical Sciences Division, Oak Ridge National Laboratory,
P. O. Box 2008, Oak Ridge, Tennessee, 37831, USA
E-mail: haybp@ornl.gov

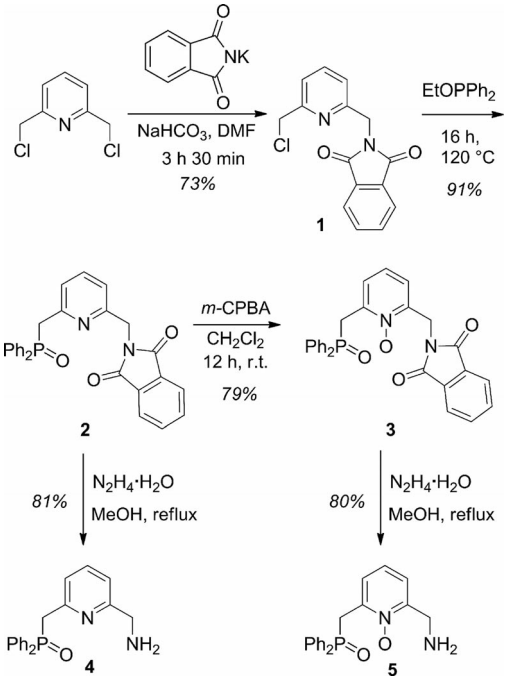
Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/ejoc.201400120.

We report here syntheses for new, functional derivatives of **B** and **C** whose chemistry will support some of the future applications.

Results and Discussion

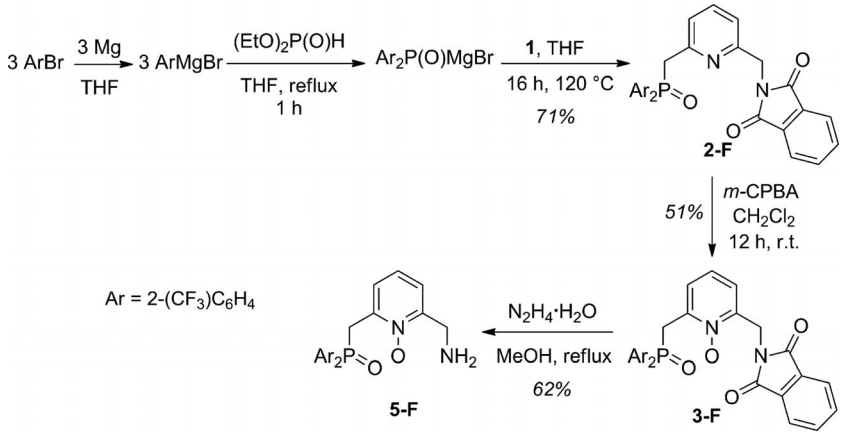
Ligand Synthesis and Structure Elucidation

The initial target molecules **4** and **5** were prepared in three and four steps, respectively (Scheme 1), and they were isolated as yellow solids with overall yields of 54 and 42%. A synthesis for the intermediate **1** has been previously reported,[6] although the modifications described herein provide a simplified procedure and improved yield. The phosphination of **1** and subsequent N-oxidation, that provide intermediates **2** and **3**, respectively, have not been described previously. Each intermediate was isolated in good yield, characterized by spectroscopic methods, and the compositions and structures of **1**–**3** were confirmed by single-crystal X-ray diffraction analyses (ORTEP views[7] in S.137–139, Supporting Information). Compounds **4** and **5** display a parent ion, [M + H$^+$], in their high-resolution (ESI) mass spectra, as well as strong IR absorptions centered at 1189 and 1193 cm^{-1}, respectively, that are assigned to the ν_{PO} stretching mode. In addition, the IR spectrum for **5** contains a band at 1234 cm^{-1} that is attributed to a ν_{NO} stretching mode. The ^{31}P NMR spectra for **4** and **5** display single resonances at δ = 30.7 and 31.5 ppm, respectively, and the ^{1}H and ^{13}C NMR spectra are consistent with the proposed structures. The X-ray diffraction analysis for **4**·H_2O (ORTEP view[7] in S.140, Supporting Information) reveals the presence of a lattice water molecule in each molecular unit, and there is extensive intermolecular hydrogen-bonding between the lattice water molecule and the phosphine oxide O-atom and the amine N-atom [N2···H2C–O2: N2···O2, 2.945(3) Å, 169.0°; O1···H2D–O2: O1···O2, 2.801(2) Å, 175.0° and O2···H2A–N2: N2···O2, 3.208(3) Å, 175.0°]. It is noted that the P=O bond length in **4**·H_2O is slightly longer [1.4955(15) Å] than the distance in **2**·MeOH [1.4915(8) Å]. This variation probably results from differences in the strengths of the hydrogen-bonding interactions between the phosphine oxide O-atoms and the lattice solvent molecules in the two structures. The crystal structure for the salt {[**4**H$^+$]Cl$^-$}·*t*BuOH was also determined (ORTEP view[7] in S.141, Supporting Information). Interesting features are that the protonation occurs on the N-atom of the 2-(aminomethyl) arm, and that the lattice *t*BuOH molecule hydrogen bonds strongly with the O-atom of the phosphine oxide fragment [O1#3···H2–O2: O1#3···O2, 2.638(1) Å, 173(2) °]. Attempts to obtain X-ray quality single crystals of **5** and {[**5**H$^+$]Cl$^-$} failed.



Scheme 1. Synthesis sequences for **4** and **5**.

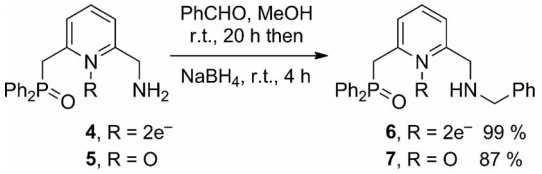
For potential solvent extraction-based separations applications it is important to have available a family of structurally related ligands with graded solubility in different organic solvents. To this end, we have developed a general procedure for the synthesis of **5** with different aryl and alkyl R substituents on the phosphoryl fragment (Scheme 2). For



Scheme 2. Synthesis sequence for **2-F**, **3-F**, and **5-F**.

this report, specifics are provided for Ar = 2-$(CF_3)C_6H_4$. In this example, each reaction step is less efficient compared with the corresponding reactions involving Ar = Ph as the substituent, and the overall yield of **5-F**, based upon 2,6-bis(chloromethyl)pyridine, was 16%. Compounds **2-F**, **3-F**, and **5-F** have spectroscopic properties comparable to those determined for **2**, **3**, and **5**.

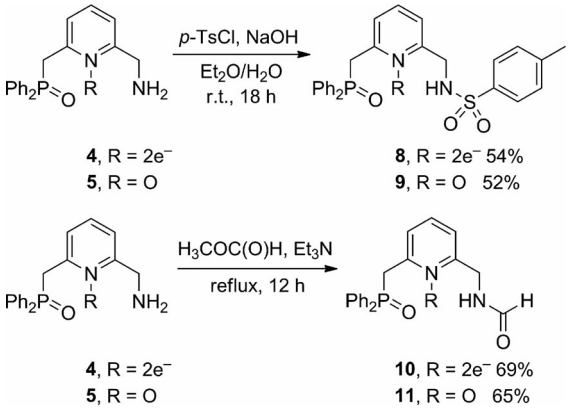
The reactivity of the aminomethyl site on **4** and **5** toward several substrates was examined. Direct alkylation, as described in the literature, with benzyl chloride or benzyl bromide in a polar solvent – tetrahydrofuran (THF)[8] or *N*,*N*-dimethylformamide (DMF)[9] –, in aqueous media,[10] by heating to reflux in MeCN,[11] or with excess ligand[8] led to over-alkylation. However, in a manner related to a synthesis described for *N*-benzyl-*N*-2-pyridylmethylamine,[12] the reactions of **4** and **5** with benzaldehyde followed by reduction of the Schiff base intermediates with $NaBH_4$ (Scheme 3), gave benzylamine derivatives **6** and **7** in high yields.



Scheme 3. Synthesis sequence for **6** and **7**.

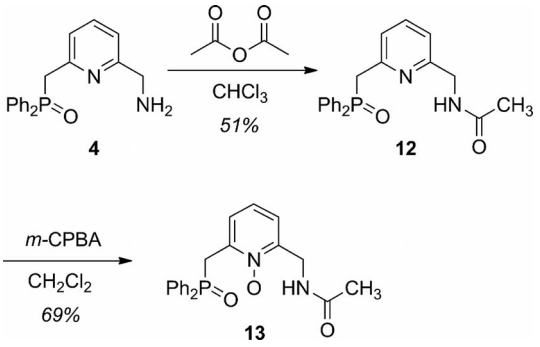
Compounds **6** and **7** were obtained as yellow and white solids, respectively, and both were characterized by HRMS, IR and NMR methods. Most notable, both products display a parent ion, $[M + H^+]$, in the mass spectra, strong ν_{PO} IR stretching frequencies, and single ^{31}P NMR resonances, δ = 31.0 and 32.2 ppm, shifted slightly downfield from **4** and **5**, respectively.

The combination of **4** and **5** with tosyl chloride, under basic conditions,[13] led to isolation of the respective sulfonamide derivatives, **8** and **9**, as white solids, in moderate yield (Scheme 4). By employing a standard approach,[14] the formamide derivatives, **10** and **11**, were obtained in good yield as white solids by reaction of **4** and **5** with methyl formate and triethylamine at reflux. The compounds were characterized by spectroscopic methods, and X-ray crystal structure determinations were completed for both compounds (ORTEP views[7] in S.142, 143, Supporting Information). The structure for **10** contains two molecules of water per asymmetric unit, and there are several short intermolecular hydrogen bond interactions between neighboring molecules of **10** [N2–H2A···O1#: N2···O1#, 2.876(2) Å, 157(2)°], as well as between lattice water molecules and **10** [N1···O3, 2.930(3) Å, 166(2)°]. The P=O and C=O bond vectors and the pyridine lone pair vector are rotated away from each other in response to electron repulsions, and the P=O and C=O bond lengths 1.4950(11) and 1.222(2) Å, respectively, are normal. The structure for **11** indicates that neighboring molecules are weakly associated, forming dimeric units through intermolecular hydrogen bonds between N–H and P=O groups [N2–H2A···O3#1: N2···O3#1, 2.892(1) Å, 171.2(2)°].



Scheme 4. Synthesis sequences for **8**, **9**, **10**, and **11**.

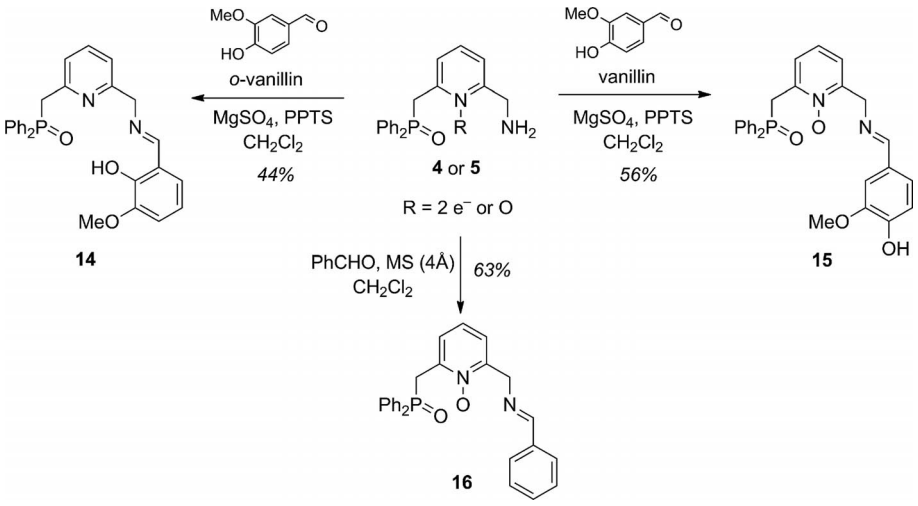
An acetamide derivative, **12**, was prepared in moderate yield and isolated as an orange oil by reaction of **4** with acetic anhydride in $CHCl_3$ (Scheme 5).[15] Subsequent N-oxidation was accomplished by reaction of **12** with *m*CPBA, and **13** was also obtained as an orange oil. An alternate approach to **13**, via reaction of **5** with acetic anhydride, was not explored.



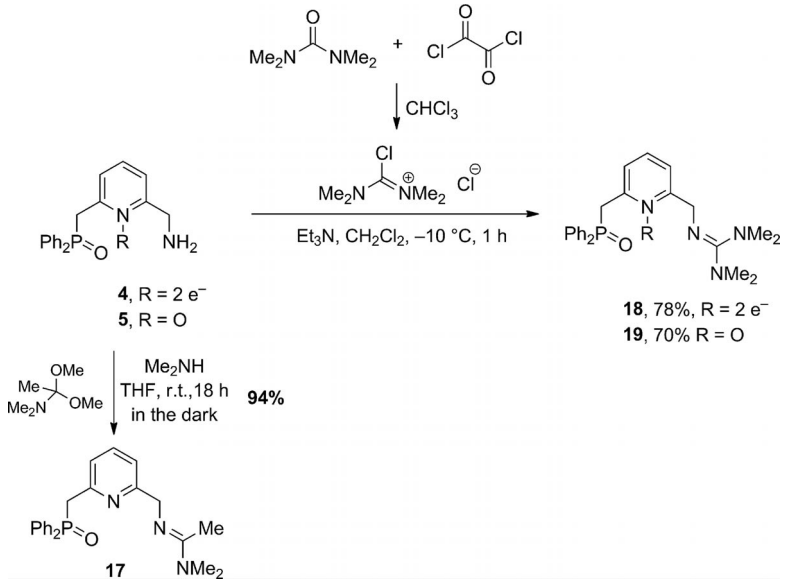
Scheme 5. Synthesis sequence for **12** and **13**.

Imines **14** and **15** were prepared by condensation of **4** with *o*-vanillin and **5** with vanillin (Scheme 6). The composition and molecular structure of **16** was confirmed by single-crystal X-ray diffraction analysis (ORTEP view in S.144, Supporting Information). The amine lone pair and the N–O and P=O bond vectors are rotated away from each other to minimize intramolecular electron pair repulsions, and the N–O (1.3082(11) Å) and P=O (1.4860(8) Å) bond lengths are comparable to those in **3**.

Amidine, **17**, and guanidine, **18** and **19**, derivatives were also obtained in good yields from **4** and **5** (Scheme 7). Attempts to prepare the amidine derivative of **5**, by using the same conditions employed with **4**, led only to partial conversion (77%), and the *N*-oxide appeared to degrade during chromatographic purification on silica gel. The *N*-oxidation of **17** was not explored. The compounds were characterized by spectroscopic methods, and the compositions and structures of **18** and **19** were confirmed by single-crystal X-ray diffraction methods (ORTEP views in S.145, 146, Supporting Information).



Scheme 6. Synthesis sequences for **14**, **15**, and **16**.

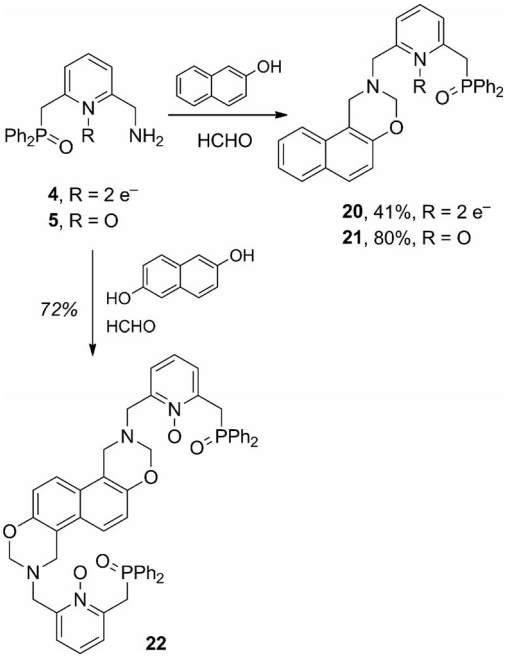


Scheme 7. Synthesis sequence for **17–19**.

The original interest in these molecules arose from efforts to employ them, or closely related analogues, as switchable polarity ligands.[16] Unfortunately, these specific examples are hydrosoluble, and they are unsuitable for this application. Alternative analogues must therefore be derived to satisfy the solubility requirements of this technique.

The Mannich condensation reactivity of **4** and **5** with formaldehyde and 2-hydroxynaphthalene or 1,5-dihydroxynaphthalene was examined, and the formation of the respective naphthoxazines, **20**–**22**, was observed (Scheme 8). The molecules were characterized by spectroscopic methods, and the data were consistent with the proposed structures. In particular, four resonances in the ^{1}H and ^{13}C NMR spectra were observed that could be confidently assigned to the four unique methylene groups in the oxazine and (phosphinoyl methyl) pyridine/(phosphinoylmethyl)-pyridine *N*-oxide fragments. The proton NMR resonances for N-CH_2-C_{naphth} and N-CH_2-O appear in the ranges 3.93–4.28 ppm and 4.81–4.92 ppm, respectively, and these shifts compare favorably with data for alkyl-functionalized naphthoxazines: N–CH_2–C_{naphth} ca. 4.1 ppm and N–CH_2–O ca. 5.0 ppm.[17] The proton NMR resonances for P(O)–CH_2–C_{pyr} and N–CH_2–C_{pyr} occur in the ranges 3.93–4.26 ppm ($J_{P,H}$ = 9.9–14.4 Hz) and 4.02–4.19 ppm, respectively, and these shifts and coupling constants are identical to data for other compounds in the **B**–**E** classes.[3] In addition, the molecular structure of **21** was confirmed by single-crystal X-ray diffraction analysis (ORTEP view in S. 147, Supporting Information). With relation to potential polymer formation, a non-isothermal DSC thermogram for **21**, recorded under a nitrogen atmosphere, displayed a broad endotherm centered at 103 °C, corresponding to melting, and a broad exotherm, reaching a maximum at 206 °C, indicative of a naphthoxazine ring-opening polyme-

rization reaction. A TGA scan showed a minor, gradual weight loss (ca. 3%) in the temperature range 50–150 °C that likely corresponds to loss of lattice water in the solid, a more abrupt weight loss event (ca. 4%) between 150 and 170 °C, followed by a gradual weight loss (10%) between 170 and 300 °C, most likely resulting from evaporation. These data are comparable to thermal data for various related naphthoxazines.[17] The ready formation of these naphthoxazine monomers and the known proclivity of benzoxazine and naphthoxazine monomers to undergo thermally promoted ring-opening polymerization[17] suggest that these molecules might be used to generate supramolecular ionophores in a fashion related to reports by Chirachanchai and co-workers.[18] The formation of robust oligomers from **21** and **22**, as well as from benzoxazine analogues, that contain the chelating fragments **C** and **D**, and the study of their ion extraction properties are in progress.



Scheme 8. Synthesis sequence for **20**–**22**.

Ligand Computational Modeling

Previous studies in our group have shown that examples of class **B**, bifunctional pyridine platform compounds, coordinate with trivalent lanthanide ions only as monodentate O_P donor ligands, whereas class **C** pyridine *N*-oxide-based compounds typically behave as strong, bidentate O_NO_P chelating ligands.[3] Similarly, class **D** trifunctional pyridine-based compounds form only bidentate O_PO_P interactions with lanthanides, but class **E** pyridine *N*-oxide-based compounds produce tridentate $O_NO_PO_P$ chelates.[3] These observations are consistent with the known thermodynamic preference of Ln^{III} ions for harder donors, e.g., phosphine oxides and pyridine *N*-oxides, as opposed to the softer pyridine *N*-atom lone pair, especially when the donor is in competition with water for coordination sites. Furthermore, the expected relatively low inherent steric hindrance to reorganization of the **B**–**E** ligand backbones to accommodate maximal denticity interactions should not seriously impact the chelate structures favored by the thermodynamic factors.[3] It is, therefore, anticipated that all of the new molecules described herein that are based upon the pyridine platform, should, driven largely by thermodynamics, act only as monodentate O_P donor ligands. On the other hand, the majority of compounds that are based on the pyridine *N*-oxide platform should form bidentate O_NO_P complexes. Potential exceptions might be encountered with the trifunctional compounds **11** and **13**, which contain an additional O_C donor site, and **15** and **19**, which possess an additional imine center. To evaluate potential steric strain, a well-tested force-field-based structure scoring approach[19] that has been successfully employed on a wide cross-section of multidonor-site ligands to search for favored steric preferences in metal ion chelation events, was employed.[3,20,21] The computations involve evaluation of structures produced in gas phase ligand-metal interactions that have low conformational energies, low degrees of induced strain, and few restricted bond rotations. The resulting calculated relative strain-free bond energies (G) per donor group can be compared for similar ligand types and used to predict favored ligand binding geometries. As an example, we chose to evaluate the 1:1 gas-phase binding of **11** with a medium-sized lanthanide cation Eu^{III}. It is first observed, not surprisingly, that the computed gas phase, global minimum free ligand structure is not ideally preorganized for tridentate $O_NO_PO_C$ chelation, most likely due to intramolecular donor atom dipole···dipole repulsions (Figure 2, a). It is also noted that, although the $[Ph_2P(O)CH_2]C_5H_3NO$ frag-

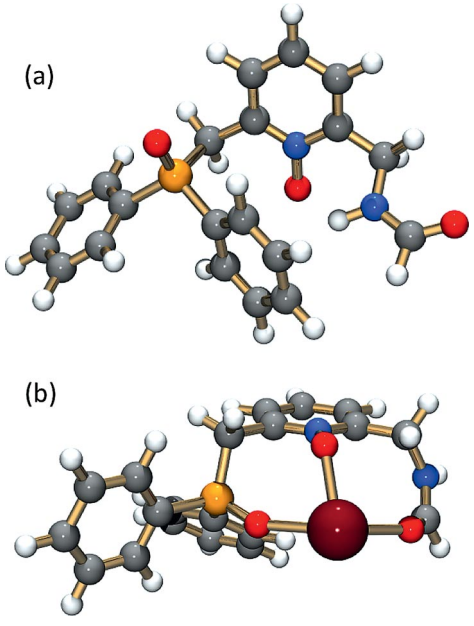


Figure 2. Computed, geometry-optimized lowest energy form for (a) **11** and (b) 1:1 tridentate chelate complex with Eu^{III}.

ment in the computed gas-phase and solid-state structures of **11** overlay relatively well, the $CH_2N(H)C(O)H$ fragment does not. The deviation from the gas-phase structure results from the dimeric intermolecular (P)O···H(N) hydrogen-bonding interactions in the solid mentioned above. Following presentation of a Eu^{III} ion to **11** in its global minimum state, tridentate $O_NO_PO_C$ structures for 1:1 complexes with low conformational energy, low degrees of induced strain, and minimal restricted bond rotations were sought. The lowest energy tridentate conformer (Figure 2, b) provided a calculated strain-free energy (G) of 3.24 kcal/mol/donor group. This can be compared with a value of 1.70 kcal/mol/donor for a 1:1 tridentate $O_NO_PO_P$ chelating complex of $[Ph_2P(O)CH_2]_2C_5H_3NO$, **E** (R = Ph). In the latter, the ligand is experimentally found to readily adopt the tridentate $O_NO_PO_P$ chelate binding mode in both 1:1 and 2:1 complexes with trivalent lanthanide and actinide ions.[3]

Given the result for modeling of the tridentate $O_NO_PO_C$ chelate condition for **11**, the strain energetics for three possible bidentate O_NO_P, O_NO_C, and O_PO_C chelate structures for **11** (Figure 3) were also evaluated and found to give estimated strain-free energies of 2.17, 3.43, and 4.56 kcal/mol/donor, respectively. Therefore, coupled with the expected order of donor strengths, P=O > N–O > amide O, it is anticipated that the bidentate O_NO_P chelate structure will be the favored coordination mode for **11** on a Ln^{III} ion.

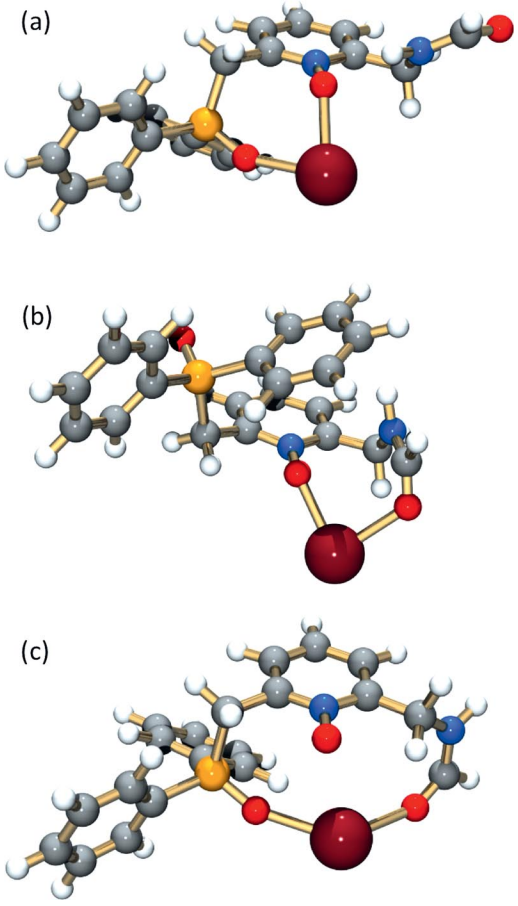


Figure 3. Computed, geometry-optimized lowest energy conformers for bidentate 1:1 chelate complexes of **11** with Eu^{III} (a) O_NO_P, (b) O_NO_C, and (c) O_PO_C modes.

Lanthanide Coordination Chemistry

The coordination interactions between several of the new multifunctional donor compounds and lanthanide(III) nitrates in methanol solution were examined. In general, solid powder samples were recovered, and each was characterized by IR spectroscopy. Selected spectra are provided in the Supporting Information (S.132–136). In all cases, a strong absorption appears in the region 1172–1153 cm^{-1} that can be assigned to ν_{PO} for a coordinated phosphine oxide group. These frequencies correspond to coordination shifts, $\Delta\nu_{PO}$ = 10–37 cm^{-1}, and they indicate, at the least, coordinative interactions of variable strength between the ligand phosphine oxide donor site and the lanthanide ion. Crystal structure determinations for three complexes, $\{[Er(\mathbf{3})(NO_3)_3(CH_3OH)]\cdot(CH_3)_2CO\}$, $[Pr(\mathbf{11})(NO_3)_3(CH_3OH)]_2$ and $[Eu(\mathbf{18}H_2^{2+})(NO_3)_4(OMe)]$, were performed, and these more completely reveal the nature of the coordination interactions in the solid-state for these ligands (Figures 4, 5, and 6). In $\{[Er(\mathbf{3})(NO_3)_3(CH_3OH)]\cdot(CH_3)_2CO\}$, the Er^{III} ion is nine-coordinate with the inner coordination sphere generated by the O-atoms in three bidentate nitrate anions, the O-atom of a methanol molecule and the phosphine oxide and pyridine *N*-oxide O-atoms of one bidentate ligand **3**. The bidentate **3**-Er^{III} interaction is nearly symmetric, as indicated by the similarity of the Er–O_P and Er–O_N bond lengths. The slightly shorter bond length involving the phosphine oxide group is consistent with its expected stronger donor strength.[3] Both P=O and N–O bond lengths in the complex are significantly elongated relative to the respective bond lengths in the free ligand. The IR spectra coordination shifts, $\Delta\nu_{PO}$ = 37 cm^{-1} and $\Delta\nu_{CO}$ = 31 cm^{-1}, are consistent with this coordination mode. The outer sphere acetone molecule is hydrogen bonded with the O-bound, inner sphere methanol: O14-H14···O1S, O14···O1S, 2.690(4) Å, 158.0°.

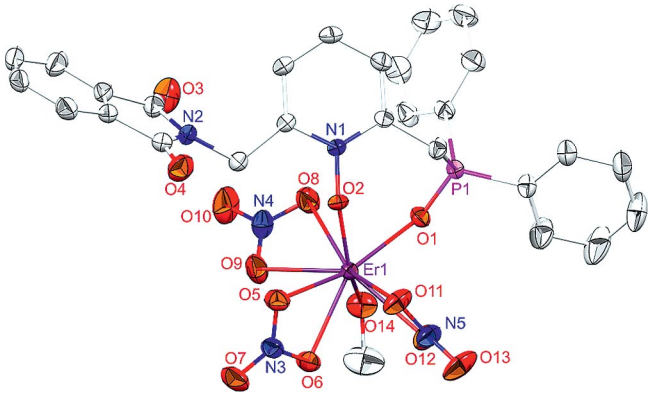


Figure 4. Molecular structure and partial atom labeling scheme for $\{[Er(\mathbf{3})(NO_3)_3(CH_3OH)]\cdot(CH_3)_2CO\}$ (outer sphere acetone and H-atoms omitted for clarity). Selected bond lengths (Å): Er1–O1 2.2537(14), Er–O2 2.2610(14), P1–O1 1.5055(15), N1–O2 1.329(2).[7]

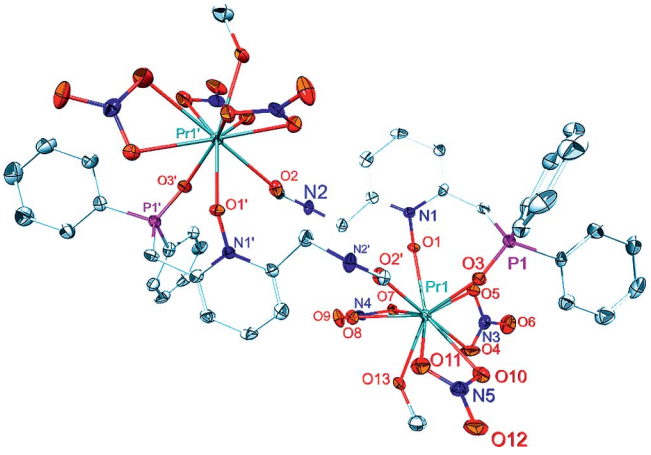


Figure 5. Molecular structure and partial atom labeling scheme for $[Pr(\mathbf{11})(NO_3)_3(CH_3OH)]_2$ (H-atoms omitted for clarity). Selected bond lengths (Å): Pr1–O3 2.388(4), Pr1–O1 2.449(4), Pr1–O2#1 2.557(4), P1–O3 1.497(4), N1–O1 1.331(5), C7–O2 1.241(6).[7]

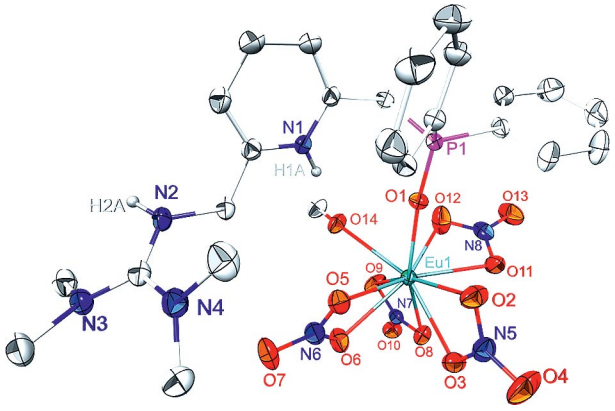


Figure 6. Molecular structure and partial atom labeling scheme for $[Eu(\mathbf{18}H_2^{2+})(NO_3)_4(OCH_3)]$ (H-atoms omitted for clarity except on N1 and N2). Selected bond lengths (Å): Eu1–O 2.297(2), Eu1–O14 2.466(2), P1–O1 1.498(2), N2–C6 1.451(4), N2–C7 1.337(4), N3–C7 1.337(4), N4–C7 1.329(4).[7]

The structure for $[Pr(\mathbf{11})(NO_3)_3(CH_3OH)]_2$ (Figure 5) is dimeric, with each Pr^{III} ion exhibiting a ten-coordinate inner sphere environment composed of O-atoms from three bidentate nitrate anions, a methanol molecule, one bidentate, O_NO_P-chelated **11** and a bridging amide carbonyl from the second $Pr(\mathbf{11})(NO_3)_3(CH_3OH)$ unit of the dimer. The bidentate O_NO_P interaction is more asymmetric than found in $\{[Er(\mathbf{3})(NO_3)_3(CH_3OH)]\cdot(CH_3)_2CO\}$, as indicated by the bond lengths Pr1–O3 2.388(4) Å involving the phosphine oxide and Pr1–O1 2.449(4) Å for the pyridine *N*-oxide fragment. The bridge interaction utilizing the amide carbonyl is weaker, as indicated by the significantly longer bond length Pr1–O2#1 2.557(4) Å. The N–O and C=O bond lengths in the respective donor groups, as expected, are elongated relative to the bond lengths in the free ligand molecule, Δ_{N-O} = 0.022 Å and ΔC=O = 0.025 Å, whereas the P=O bond lengthening, $\Delta_{P=O}$ = 0.004 Å, is relatively small. The energy difference between the observed dimeric, bidentate O_NO_P chelate-O_C bridge structure and a monomeric, tridentate $O_NO_PO_C$ structure is probably small, and the utilization of the former ligand binding mode may mirror the computed tridentate ligand strain described above. It is possible that, under different synthesis conditions and/or with different counterions, the tridentate chelation mode for **11** may appear. Such structure selection changes have been observed with other complexes that involve Ln^{III} ions and related chelating ligands developed in our group.[3] Lastly, the structure is consistent with the small IR coordination shifts recorded for the complex: $\Delta\nu_{NO}$ = 28 cm^{-1}, $\Delta\nu_{CO}$ = 22 cm^{-1}, and $\Delta\nu_{PO}$ = 10 cm^{-1}.

Amidines and guanidines are known to be strong organic bases.[22–24] With particular relevance to our study, hybrid pyridine/guanidine ligands[25–27] have been observed to generate chelating structures on *d*- and *f*-block metal cations. Therefore, it was anticipated that the new hybrid ligands, **18** and **19**, might act as bidentate O_NO_P or O_PN_{guan}, or tridentate $O_NO_PN_{guan}$ ligands. However, a monodentate O_P structure (Figure 6) was observed for the complex formed from the 1:1 combination of $Eu(NO_3)_3{\cdot}xH_2O$ and **18** in MeOH solution. The structure reveals a ten coordinate environment for the Eu^{III} cation generated by O-atoms from four bidentate nitrate anions, the O-atom from a methoxide anion and the phosphine oxide O-atom of a monodentate, doubly protonated cation, $\mathbf{18}H^{2+}$. This results in a formula $[Eu(\mathbf{18}H_2^{2+})(NO_3)_4(CH_3O)]$ instead of the neutral ligand formula $[Eu(\mathbf{18})(NO_3)_3(CH_3OH)]$. The bond lengthening in the P=O bond upon coordination, $\Delta_{P=O}$ = 0.011 Å, is modest and consistent with a small coordination shift in the IR spectrum for the complex relative to the free ligand, $\Delta\nu_{PO}$ = 19 cm^{-1}.

Conclusions

A general synthetic procedure has been developed for 6-(methylphosphine oxide) decorated 2-(aminomethyl)pyridine and pyridine *N*-oxide compounds, **4** and **5**, and some of the reactivity of the aminomethyl center has been surveyed for the purpose of defining approaches for attaching the **B**- and **C**-class ligand fragments to solid supports and/or for using the fragments in switchable polar/nonpolar, organic-solvent-free separations constructs. These initial results and the ligand/Ln^{III} ion coordination chemistry encourage continuing efforts to use **4** and **5** to prepare materials that will have useful performance characteristics especially for intralanthanide ion separations.

Experimental Section

General Information: Organic reagents were purchased from Aldrich Chemical Co., and they were used as received. Solvents were purchased from VWR, and dried by standard procedures. The lanthanide nitrates were purchased from Ventron. Reactions were performed under a dry nitrogen atmosphere by using Schlenk methods unless noted otherwise. Infrared spectra were recorded from KBr pellets with a Bruker Tensor 27 FTIR spectrometer. The NMR spectra were recorded with Avance 300 and 500 spectrometers by using Me_4Si (^1H and ^{13}C) and 85% H_3PO_4 (^{31}P) as chemical shift

standards. Downfield shifts were assigned +δ values. Mass spectra were obtained from the UNM Mass Spectrometry Center, and elemental analyses were performed by Galbraith Laboratories.

2-[(6-Chloromethyl)pyridin-2-yl]isoindoline-1,3-dione (1): A sample of 2,6-bis(chloromethyl)pyridine (26.46 g, 150.3 mmol) was dissolved in DMF (1 L), and potassium phthalimide (13.91 g, 75.12 mmol) and $NaHCO_3$ (6.31 g, 75.1 mmol) were added in one portion with stirring (23 °C, 3 h). The resulting mixture was divided into three equal portions, and each was poured into a water/ice mixture (3 × 1 L) and stirred (30 min). The precipitates were collected by filtration, washed with Et_2O (3 × 100 mL) and crystallized from hot MeOH to give **1**, yield 15.7 g (73%); white powder; m.p. 124–125 °C. X-ray quality single crystals were obtained by slow evaporation of a MeOH solution (23 °C). ^{1}H NMR (300 MHz, $CDCl_3$, 298 K): δ = 7.87 (dd, $J_{H,H}$ = 5.4, 3.0 Hz, 2 H, H-10), 7.73 (dd, $J_{H,H}$ = 5.4, 3.0 Hz, 2 H, H-11), 7.65 (t, $J_{H,H}$ = 7.8 Hz, 1 H, H-4), 7.35 (d, $J_{H,H}$ = 7.8 Hz, 1 H, H-3), 7.16 (d, $J_{H,H}$ = 7.8 Hz, 1 H, H-5), 4.99 (s, 2 H, H-1), 4.57 (s, 2 H, H-7) ppm. ^{13}C{^{1}H} NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 168.1 (C-8), 156.6 (C-6), 155.1 (C-2), 137.8 (C-4), 134.2 (C-11), 132.2 (C-9), 123.6 (C-10), 121.5 (C-3), 120.5 (C-5), 46.7 (C-7), 42.9 (C-1) ppm. FTIR (KBr): $\tilde{\nu}$ = 3011, 1771, 1705 ($\nu_{C=O}$), 1594, 1575, 1462, 1420, 1392, 1337, 1318, 1284, 1189, 1107, 1086, 993, 952, 930, 897, 798, 760, 741, 721, 683, 642, 604, 593 cm^{-1}. HRMS (ESI$^+$): *m*/*z* (%) = 287.0583 [M + H$^+$] (100), $C_{15}H_{12}ClN_2O_2$ requires 287.0582; 309.0405 [M + Na$^+$] (46), $C_{15}H_{11}ClN_2NaO_2$ requires 309.0401. $C_{15}H_{11}ClN_2O_2$ (286.71): calcd. C 62.84, H 3.87, N 9.77; found C 62.87, H 3.88, N 9.79.

2-(6-{[(Diphenylphosphoryl)methyl]pyridin-2-yl}methyl)isoindoline-1,3-dione (2): A solution of **1** (15 g, 52 mmol) in ethyl diphenylphosphinite (22.6 mL, 105 mmol) was heated at 120 °C for 16 h. The resulting slightly brown mixture was cooled (23 °C), and Et_2O (100 mL) was added. The mixture was triturated, and the white precipitate was collected and washed with Et_2O (2 × 200 mL) to give **2**, yield 21.6 g (91%); white powder; m.p. 148–150 °C. X-ray quality single crystals were obtained by slow evaporation of a MeOH solution (23 °C). ^{31}P{^{1}H} NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 30.8 ppm. ^{1}H NMR (300 MHz, $CDCl_3$, 298 K): δ = 7.85 (dd, $J_{H,H}$ = 5.4, 3.0 Hz, 2 H, H-10), 7.71 (dd, $J_{H,H}$ = 5.4, 3.0 Hz, 2 H, H-11), 7.68–7.61 (m, 4 H, H-13), 7.46 (t, $J_{H,H}$ = 7.8 Hz, 1 H, H-4), 7.37–7.27 (m, 7 H, H-5,14,15), 7.03 (d, $J_{H,H}$ = 7.5 Hz, 1 H, H-3), 4.81 (s, 2 H, H-1), 3.82 (d, $J_{H,P}$ = 14.4 Hz, 2 H, H-7) ppm. ^{13}C{^{1}H} (75.4 MHz, $CDCl_3$, 298 K): δ = 167.9 (C-8), 154.8 (C-2), 152.6 (d, $J_{C,P}$ = 6.6 Hz, C-6), 137.1 (C-4), 134.1 (C-11), 132.3 (d, $J_{C,P}$ = 98.9 Hz, C-12), 132.2 (C-9), 131.7 (C-15), 131.1 (d, $J_{C,P}$ = 9.5 Hz, C-13), 128.3 (d, $J_{C,P}$ = 12.0 Hz, C-14), 123.8 (d, $J_{C,P}$ = 3.4 Hz, C-5), 123.4 (C-10), 119.6 (C-3), 42.8 (C-1), 41.0 (d, $J_{C,P}$ = 64.1 Hz, C-7) ppm. FTIR (KBr): $\tilde{\nu}$ = 1771 ($\nu_{C=O}$), 1713 ($\nu_{C=O}$), 1589, 1572, 1454, 1437, 1423, 1396, 1362, 1327, 1282, 1189 ($\nu_{P=O}$), 1116, 1071, 1027, 992, 950, 902, 822, 802, 748, 731, 708, 695, 649, 616, 540, 520, 485 cm^{-1}. HRMS (ESI$^+$): *m*/*z* (%) = 453.1377 [M + H$^+$] (84), $C_{27}H_{22}N_2O_3P$ requires 453.1363; 475.1208 [M + Na$^+$] (17), $C_{27}H_{21}N_2NaO_3P$ requires 475.1182. $C_{27}H_{21}N_2O_3P$·(CH_3OH) (484.49): calcd. C 69.41, H 5.20, N 5.78; found C 68.84, H 5.13, N 5.18.

2-{6-[({Bis[2-(trifluoromethyl)phenyl]phosphoryl}methyl)pyridin-2-yl]methyl}isoindoline-1,3-dione (2-F): A solution of 2-bromobenzotrifluoride (9.6 mL, 71 mmol) in anhydrous THF (52 mL) was combined dropwise with a suspension of magnesium (1.71 g, 70.6 mmol) in anhydrous THF (18 mL). The temperature rose during the addition. Following addition, the mixture was stirred (1 h), then cooled to 23 °C, and a solution of diethylphosphite (2.3 mL, 18 mmol) in anhydrous THF (32 mL) was added dropwise. The mixture was heated to reflux (1 h), and then cooled (23 °C). A solution of 2,6-bis(chloromethyl)pyridine **1** (5.06 g, 17.7 mmol) in anhydrous THF (62 mL) was added dropwise at 23 °C, and the mixture was stirred and heated to reflux (12 h). The resulting mixture was quenched with a saturated aqueous solution of NH_4Cl (100 mL), the aqueous phase was separated, and then extracted with CH_2Cl_2 (3 × 100 mL). The organic phases were combined, dried with $MgSO_4$, and concentrated. The residue was purified by flash chromatography on silica gel (CH_2Cl_2/MeOH, 98:2) to afford **2-F**, yield 7.6 g (71%); white foam. ^{31}P{^{1}H} NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 30.7 ppm. ^{1}H NMR (300 MHz, $CDCl_3$, 298 K): δ = 8.10–8.02 (m, 2 H, CH_{Ar}), 7.82 (dd, $J_{H,H}$ = 5.4, 3.0 Hz, 2 H, CH_{Ar}), 7.71 (dd, $J_{H,H}$ = 5.4, 3.3 Hz, 2 H, CH_{Ar}), 7.64–7.60 (m, 2 H, CH_{Ar}), 7.56–7.52 (m, 4 H, CH_{Ar}), 7.49 (t, $J_{H,H}$ = 7.8 Hz, 1 H, CH_{Py}), 7.40–7.37 (m, 1 H, CH_{Py}), 7.02 (d, $J_{H,H}$ = 7.8 Hz, 1 H, CH_{Py}), 4.76 (s, 2 H, H-1), 3.95 (d, $J_{H,P}$ = 14.7 Hz, 2 H, H-7) ppm. ^{13}C{^{1}H} (75.4 MHz, $CDCl_3$, 298 K): δ = 167.9 (C-14), 154.6 (C-2), 151.9 (d, $J_{C,P}$ = 7.1 Hz, C-6), 137.0 (C_{Ar}), 134.3 (C_{Ar}), 134.2 (C_{Ar}), 134.1 (C-16), 132.2 (C_{Ar}), 132.0 (C_{qAr}), 131.8 (C_{Ar}), 131.3 (C_{Ar}), 131.2 (C_{Ar}), 130.8 (C_{qAr}), 127.5–127.3 (m, C_{Ar}), 124.8 (d, $J_{C,P}$ = 3.2 Hz, C_{Py}), 123.5 (q, $J_{C,F}$ = 273.8 Hz, C-18), 123.5 (C-17), 119.6 (C_{Py}), 42.5 (C-1), 41.9 (d, $J_{C,P}$ = 69.2 Hz, C-7) ppm. FTIR (KBr): $\tilde{\nu}$ = 1775 (ν_{CO}), 1718 (ν_{CO}), 1593, 1576, 1469, 1456, 1424, 1395, 1314, 1267, 1176 (ν_{PO}), 1120, 1036, 994, 953, 910, 828, 771, 729, 645, 597, 530, 498 cm^{-1}. HRMS (ESI$^+$): *m*/*z* (%) = 589.1114 [M + H$^+$] (18), $C_{29}H_{20}F_6N_2O_3P$ requires 589.1110; 611.0937 [M + Na$^+$] (100), $C_{29}H_{19}F_6N_2NaO_3P$ requires 611.0930; 627.0668 [M + K$^+$] (20) $C_{29}H_{19}F_6KN_2O_3P$ requires 627.0669.

2-[(1,3-Dioxoisoindolin-2-yl)methyl]-6-[(diphenylphosphoryl)methyl]-pyridine 1-Oxide (3): To a solution of **2** (15 g, 33 mmol) in CH_2Cl_2 (500 mL) was added *m*-chloroperoxybenzoic acid (77 wt.-%, 11.14 g, 49.72 mmol). The mixture was stirred (23 °C, 12 h) and then washed with an aqueous solution of NaOH (2N, 3 × 15 mL) and water (2 × 10 mL). The organic phase was dried ($MgSO_4$), filtered, and the solvent was removed by vacuum evaporation to give **3**, yield 12.3 g (79%); white powder; m.p. 184–186 °C. ^{31}P{^{1}H} NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 31.6 ppm. ^{1}H NMR (300 MHz, $CDCl_3$, 298 K): δ = 7.80 (dd, $J_{H,H}$ = 5.4, 3.0 Hz, 2 H, H-10), 7.78–7.71 (m, 4 H, H-13), 7.70–7.64 (m, 3 H, H-5,11), 7.40–7.28 (m, 6 H, H-14,15), 7.00 (t, $J_{H,H}$ = 7.8 Hz, 1 H, H-4), 6.90 (d, $J_{H,H}$ = 7.8 Hz, 1 H, H-3), 4.88 (s, 2 H, H-1), 4.19 (d, $J_{H,P}$ = 14.1 Hz, 2 H, H-7) ppm. ^{13}C{^{1}H} NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 167.4 (C-8), 145.4 (C-2), 144.2 (d, $J_{C,P}$ = 5.7 Hz, C-6), 134.3 (C-11), 132.0 (d, $J_{C,P}$ = 1.9 Hz, C-15), 131.8 (C-9), 131.7 (d, $J_{C,P}$ = 101.6 Hz, C-12), 130.7 (d, $J_{C,P}$ = 9.9 Hz, C-13), 128.4 (d, $J_{C,P}$ = 12.1 Hz, C-14), 126.1 (d, $J_{C,P}$ = 3.8 Hz, C-5), 124.4 (C-4), 123.5 (C-10), 122.2 (C-3), 37.7 (C-1), 31.2 (d, $J_{C,P}$ = 65.9 Hz, C-7) ppm. FTIR (KBr): $\tilde{\nu}$ = 1801, 1771 ($\nu_{C=O}$), 1712 ($\nu_{C=O}$), 1612, 1590, 1566, 1492, 1471, 1438, 1416, 1353, 1310, 1274, 1244 (ν_{N-O}), 1198 ($\nu_{P=O}$), 1115, 1027, 995, 951, 911, 846, 823, 808, 770, 754, 719, 693, 640, 595, 570, 531, 505, 481 cm^{-1}. HRMS (ESI$^+$): *m*/*z* (%) = 469.1312 [M + H$^+$] (69), $C_{27}H_{22}N_2O_4P$ requires 469.1312; 491.1131 [M + Na$^+$] (100), $C_{27}H_{21}N_2NaO_4P$ requires 491.1131; 507.0880 [M + K$^+$] (12), $C_{27}H_{21}KN_2O_4P$ requires 507.0871. $C_{27}H_{21}N_2O_4P$ (468.44): calcd. C 69.23, H 4.52, N 5.98; found C 68.55, H 4.54, N 5.89.

2-({Bis[2-(trifluoromethyl)phenyl]phosphoryl}methyl)-6-[(1,3-dioxoisoindolin-2-yl)methyl]pyridine 1-Oxide (3-F): To a solution of **2-F** (2.77 g, 4.71 mmol) in CH_2Cl_2 (70 mL) was added *m*-chloroperoxybenzoic acid (77 wt.-%, 1.58 g, 7.06 mmol). The reaction mixture was stirred (23 °C, 18 h), and then an aqueous saturated solution of $NaHCO_3$ (70 mL) was added. The aqueous layer was ex-

tracted with CH_2Cl_2 (3× 50 mL), and the combined organic layers were washed with brine, dried with $MgSO_4$, and concentrated. The residue was purified by flash chromatography on silica gel (CH_2Cl_2/MeOH, 98:2) to afford **3-F** as a yellow foam, yield 1.45 g (51%). X-ray quality single crystals were obtained by slow evaporation of a MeOH solution (23 °C). $^{31}P\{^1H\}$ NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 32.1 ppm. ^1H NMR (300 MHz, $CDCl_3$, 298 K): δ = 8.08–8.04 (m, 2 H, CH_{Ar}), 7.85–7.57 (m, 11 H, CH_{Ar}), 7.09 (t, $J_{H,H}$ = 7.2 Hz, 1 H, H-4), 6.93 (d, $J_{H,H}$ = 6.3 Hz, 1 H, H-3), 4.86 (s, 2 H, H-1), 4.37 (d, $J_{H,P}$ = 14.4 Hz, 2 H, H-7) ppm. $^{13}C\{^1H\}$ NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 167.5 (C-14), 145.6 (C-2), 143.2 (d, $J_{C,P}$ = 6.5 Hz, C-6), 134.4 (C-17), 134.0 (d, $J_{C,P}$ = 65.4 Hz, C-8), 133.6 (d, $J_{C,P}$ = 8.8 Hz, C-13), 132.3 (C-11), 131.9 (C-4), 131.3 (d, $J_{C,P}$ = 11.0 Hz, C-12), 130.3 (C-10), 127.7 (C-15), 126.1 (q, $J_{C,F}$ = 236.1 Hz, C_{CF3}), 124.5 (C-5), 123.7 (C-16), 122.2 (C-3), 37.7 (C-7), 32.0 (d, $J_{C,P}$ = 72.1 Hz, C-1) ppm. FTIR (KBr): $\tilde{\nu}$ = 3080, 3031, 1956, 1776 ($\nu_{C=O}$), 1719 ($\nu_{C=O}$), 1617 ($\nu_{C=O}$), 1593, 1567, 1492, 1473, 1437, 1417, 1390, 1349, 1314, 1263, 1237 (ν_{N-O}), 1179 ($\nu_{P=O}$), 1122, 1036, 951, 913, 893, 843, 820, 788, 775, 763, 715, 700, 678, 646, 599, 552, 535, 514 cm^{-1}. HRMS (ESI^+): *m/z* (%) = 605.1059 [M + H^+] (100), $C_{29}H_{20}F_6N_2O_4P$ requires 605.1059; 627.0878 [M + Na^+] (49), $C_{29}H_{19}F_6N_2NaO_4P$ requires 627.0879. $C_{29}H_{19}F_6N_2O_4P$ (604.44): calcd. C 57.63, H 3.17, N 4.63; found C 56.84, H 3.11, N 4.50.

{[6-(Aminomethyl)pyridin-2-yl]methyl}diphenylphosphine Oxide (4): To a stirred solution of **2** (6.5 g, 14 mmol) in methanol (50 mL) was added, under a nitrogen atmosphere, hydrazine hydrate (1.8 mL, 29 mmol). The reaction mixture was stirred (90 °C, 16 h), and the volatiles were then removed by vacuum evaporation. The residue was dissolved in CH_2Cl_2 (100 mL) and washed with water (150 mL). The aqueous layer was extracted with CH_2Cl_2 (2× 100 mL), and the combined organic layers were washed with brine (100 mL), dried ($MgSO_4$), and filtered to give an orange oil. The oil was dissolved in CH_2Cl_2 (5 mL) and Et_2O (30 mL) was added. Trituration and filtration afforded **4** as a yellow solid, yield 3.75 g (81%); m.p. > 280 °C. Soluble: acetone, chloroform, CH_2Cl_2, MeOH, DMF, DMSO and hot acetonitrile; insoluble: Et_2O and hexane. X-ray quality single crystals of **4**·H_2O were obtained by slow evaporation of a CH_2Cl_2 solution. Crystals of [**4**H^+][Cl^-]·*t*BuOH were obtained by slow evaporation of a mixed solvent system containing MeOH, *t*BuOH, CH_2Cl_2 and Et_2O (23 °C). $^{31}P\{^1H\}$ (121.49 MHz, $CDCl_3$, 298 K): δ = 30.7 ppm. ^1H NMR (300 MHz, $CDCl_3$, 298 K): δ = 7.84–7.75 (m, 4 H, H-9), 7.45–7.26 (m, 7 H, H-4,10,11), 7.23 (d, $J_{H,H}$ = 7.8 Hz, 1 H, H-3), 6.96 (d, $J_{H,H}$ = 7.8 Hz, 1 H, H-5), 3.89 (d, $J_{H,P}$ = 14.1 Hz, 2 H, H-7), 3.70 (s, 2 H, H-1), 1.49 (s, 2 H, NH_2) ppm. $^{13}C\{^1H\}$ NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 161.4 (C-2), 152.0 (d, $J_{C,P}$ = 7.5 Hz, C-6), 137.0 (C-4), 132.5 (d, $J_{C,P}$ = 104.7 Hz, C-8), 131.8 (C-11), 131.3 (d, $J_{C,P}$ = 9.4 Hz, C-9), 128.5 (d, $J_{C,P}$ = 11.9 Hz, C-10), 123.1 (d, $J_{C,P}$ = 3.7 Hz, C-3), 119.2 (d, $J_{C,P}$ = 2.3 Hz, C-5), 47.3 (C-1), 40.9 (d, $J_{C,P}$ = 64.7 Hz, C-7) ppm. FTIR (KBr): $\tilde{\nu}$ = 3418, 3053, 1589, 1572, 1483, 1453, 1436, 1396, 1270, 1189 ($\nu_{P=O}$), 1119, 1103, 1071, 1027, 995, 925, 831, 745, 719, 695, 523, 505 cm^{-1}. HRMS (ESI^+): *m/z* (%) = 323.1313 [M + H^+] (100), $C_{19}H_{20}N_2OP$ requires 323.1308; 345.1118 [M + Na^+] (7), $C_{19}H_{19}N_2NaOP$ requires 345.1127.

2-(Aminomethyl)-6-[(diphenylphosphoryl)methyl]pyridine 1-Oxide (5): A sample of **3** (12 g, 26 mmol) in MeOH (150 mL) was combined with hydrazine hydrate (3.2 mL, 51 mmol), and the mixture was stirred at 90 °C for 16 h. The resulting mixture was evaporated to dryness, the residue was dissolved in CH_2Cl_2 (150 mL), and the solution washed with water (200 mL). The aqueous layer was extracted with CH_2Cl_2 (2× 10 mL), and the combined organic layers were washed with brine (50 mL), dried ($MgSO_4$), and filtered to give **5** as a yellow solid, yield 6.89 g (80%); m.p. > 280 °C. Soluble: acetone, chloroform, CH_2Cl_2, MeOH, DMF, DMSO and hot acetonitrile; insoluble: Et_2O and hexane. $^{31}P\{^1H\}$ NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 31.5 ppm. ^1H NMR (300 MHz, $CDCl_3$, 298 K): δ = 7.84–7.77 (m, 4 H, H-9), 7.77–7.62 (m, 1 H, H-5), 7.47–7.34 (m, 6 H, H-10,11), 7.17–7.07 (m, 2 H, H-3,4), 4.22 (d, $J_{H,P}$ = 14.1 Hz, 2 H, H-7), 3.82 (s, 2 H, H-1), 1.85 (s, 2 H, NH_2) ppm. $^{13}C\{^1H\}$ NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 152.0 (C-2), 144.0 (C-6), 132.1 (C-11), 132.0 (d, $J_{C,P}$ = 101.6 Hz, C-8), 131.0 (d, $J_{C,P}$ = 9.9 Hz, C-9), 128.5 (d, $J_{C,P}$ = 12.1 Hz, C-10), 125.8 (d, $J_{C,P}$ = 4.3 Hz, C-5), 125.1 (C-4), 122.7 (C-3), 43.0 (C-1), 31.7 (d, $J_{C,P}$ = 65.7 Hz, C-7) ppm. FTIR (KBr): $\tilde{\nu}$ = 3387, 3306, 1614, 1589, 1568, 1486, 1437, 1407, 1392, 1365, 1314, 1262, 1234 (ν_{N-O}), 1193 ($\nu_{P=O}$), 1121, 1073, 1027, 996, 972, 919, 901, 850, 823, 784, 763, 740, 720, 695, 617, 600, 573, 550, 517, 463, 425 cm^{-1}. HRMS (ESI^+): *m/z* (%) = 339.1257 [M + H^+] (100), $C_{19}H_{20}N_2O_2P$ requires 339.1256; 361.1084 [M + Na^+] (46), $C_{19}H_{19}N_2NaO_2P$ requires 361.1082.

2-(Aminomethyl)-6-({bis[2-(trifluoromethyl)phenyl]phosphoryl}-methyl)pyridine 1-Oxide (5-F): A sample of **3-F** (5.5 g, 9.1 mmol) in MeOH (41 mL) was combined under a nitrogen atmosphere with hydrazine hydrate (31 mL), and the mixture was stirred at 90 °C for 18 h. The solvent was evaporated to dryness, and the residue was purified by flash chromatography (CH_2Cl_2/MeOH, 98:2) to afford **5-F** as a yellow powder, yield 2.68 g (62%); m.p. 198–200 °C. X-ray quality single crystals were obtained by slow evaporation of a MeOH solution (23 °C). $^{31}P\{^1H\}$ NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 31.7 ppm. ^1H NMR (300 MHz, $CDCl_3$): δ = 8.13 (dd, $J_{H,H}$ = 14.4, 6.9 Hz, 2 H, H-13), 7.77–7.70 (m, 3 H, H-5,12), 7.64–7.55 (m, 4 H, H-10,11), 7.22–7.19 (m, 1 H, H-3), 7.14 (t, $J_{H,H}$ = 7.5 Hz, 1 H, H-4), 4.39 (d, $J_{H,P}$ = 14.4 Hz, 2 H, H-7), 3.82 (s, 2 H, H-1), 1.83 (s, 2 H, NH_2) ppm. $^{13}C\{^1H\}$ NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 151.9 (C-2), 143.0 (d, $J_{C,P}$ = 6.9 Hz, C-6), 133.9 (d, $J_{C,P}$ = 8.9 Hz, C-13), 132.2 (C-11), 131.5 (d, $J_{C,P}$ = 129.7 Hz, C-8), 132.2–131.9 (m, C-9), 131.9 (C-4), 131.3 (d, $J_{C,P}$ = 11.7 Hz, C-12), 127.7–127.3 (m, C-10), 125.1 (C-5), 123.5 (q, $J_{C,F}$ = 274.1 Hz, C-14), 123.0 (C-3), 43.1 (C-1), 32.2 (d, $J_{C,P}$ = 71.4 Hz, C-7) ppm. FTIR (KBr): $\tilde{\nu}$ = 3426, 3346, 3073, 3028, 2989, 2872, 1625, 1592, 1489, 1404, 1311, 1276, 1259, 1232 (ν_{N-O}), 1189 ($\nu_{P=O}$), 1173, 1149, 1123, 1035, 921, 845, 815, 777, 736, 716, 699, 683, 644, 598, 520, 500 cm^{-1}. HRMS (ESI^+): *m/z* (%) = 475.1002 [M + H^+] (100), $C_{21}H_{18}F_6N_2O_2P$ requires 475.1005. $C_{21}H_{17}F_6N_2O_2P$ (474.34): calcd. C 53.17, H 3.61, N 5.91; found C 52.65, H 3.82, N 5.80.

{6-[(Benzylamino)methyl]pyridin-2-yl}methyldiphenylphosphine Oxide (6): To a solution of **4** (436 mg, 1.35 mmol) in MeOH (2.5 mL) was added a solution of benzaldehyde (0.15 mL, 1.4 mmol) in MeOH (1.5 mL). The solution was stirred (23 °C, 20 h) and $NaBH_4$ (41 mg, 1.1 mmol) was added in portions. The reaction mixture was stirred (4 h, 23 °C), then acidified with HCl (6 M, 2 mL), and the solvents were evaporated from the mixture to dryness under reduced pressure. The crude product was purified by flash chromatography on silica gel (CH_2Cl_2/MeOH, 98:2 to 94:6) to give **6**, yield 440 mg (99%); yellow foam; m.p. 132–134 °C. $^{31}P\{^1H\}$ NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 31.0 ppm. ^1H NMR (300 MHz, $CDCl_3$, 298 K): δ = 8.78 (br. s, 1 H, NH), 7.77 (dd, $J_{H,H}$ = 11.4, 7.5 Hz, 4 H, H-9), 7.50 (t, $J_{H,H}$ = 7.8 Hz, 1 H, H-4), 7.39–7.36 (m, 9 H, H-5,10,11,15), 7.27–7.26 (m, 3 H, H-14,16), 7.11 (d, $J_{H,H}$ = 7.5 Hz, 1 H, H-3), 3.99 (d, $J_{H,P}$ = 13.8 Hz, 2 H, H-7), 3.92 (s, 2 H, H-12), 3.77 (s, 2 H, H-1) ppm. ^{13}C NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 152.6 (d, $J_{C,P}$ = 7.8 Hz, C-6), 152.0 (d, $J_{C,P}$ = 7.2 Hz, C-2), 137.6 (C-4), 132.3 (C-13), 132.0 (C-11), 131.8 (d, $J_{C,P}$ = 104.3 Hz, C-8), 131.2 (d, $J_{C,P}$ = 9.5 Hz, C-9), 130.1 (C-15), 128.8 (C-16), 128.7 (C-14), 128.6 (d, $J_{C,P}$ = 12.1 Hz, C-10), 124.6 (C-5),

121.4 (C-3), 50.3 (C-1), 49.6 (C-12), 40.1 (d, $J_{C,P}$ = 64.4 Hz, C-7) ppm. FTIR (KBr): $\tilde{\nu}$ = 3420, 3054, 1692, 1576, 1483, 1456, 1437, 1397, 1280, 1180 ($\nu_{P=O}$), 1120, 1104, 1071, 1027, 996, 927, 834, 784, 722, 697, 611, 543, 522 cm^{-1}. HRMS (ESI^+): *m*/*z* (%) = 413.1781 [M + H^+] (100). $C_{26}H_{26}N_2OP$ requires 413.1777.

2-[(Benzylamino)methyl]-6-[(diphenylphosphoryl)methyl]pyridine 1-Oxide (7): To a solution of **5** (170 mg, 0.50 mmol) in MeOH (2 mL) was added a solution of benzaldehyde (54 μL, 0.53 mmol) in MeOH (1 mL). The reaction was stirred (23 °C, 18 h), and the resulting mixture was treated with $NaBH_4$ (15.2 mg, 0.4 mmol). The reaction mixture was stirred (4 h, 23 °C), acidified with HCl (6 M, 2 mL) and the solvents were evaporated to dryness under reduced pressure. The crude product was purified by flash chromatography on silica gel (CH_2Cl_2/MeOH, 95:5 to 90:10) to give **7**, yield 187 mg (87%); white powder; m.p. 96–98 °C. $^{31}P\{^1H\}$ NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 32.2 ppm. ^1H NMR (300 MHz, $CDCl_3$, 298 K): δ = 10.10 (br. s, 1 H, NH), 7.74–7.68 (m, 4 H, H-9), 7.56–7.53 (m, 4 H, CH_{Ar}), 7.42–7.37 (m, 9 H, H_{Ar}), 7.26–7.24 (m, 1 H, H-3), 4.31 (s, 2 H, H-12), 4.15 (s, 2 H, H-1), 4.13 (d, $J_{H,P}$ = 13.8 Hz, 2 H, H-7) ppm. ^{13}C NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 144.4 (d, $J_{C,P}$ = 6.4 Hz, C-6), 141.6 (C-2), 132.5 (C-11), 131.0 (d, $J_{C,P}$ = 108.3 Hz, C-8), 131.0 (d, $J_{C,P}$ = 9.6 Hz, C-9), 130.6 (C-13), 130.3 (C-15), 129.6 (C-16), 129.1 (C-14), 128.8 (d, $J_{C,P}$ = 12.1 Hz, C-10), 128.6 (C-3 or C-4 or C-5), 127.4 (C-3 or C-4 or C-5), 127.1 (C-3 or C-4 or C-5), 51.1 (C-12), 46.9 (C-1), 32.1 (d, $J_{C,P}$ = 65.6 Hz, C-7) ppm. FTIR (KBr): $\tilde{\nu}$ = 3410, 3054, 1589, 1488, 1457, 1437, 1220 (ν_{N-O}), 1178 ($\nu_{P=O}$), 1120, 1071, 1027, 997, 924, 853, 820, 792, 726, 697, 641, 594, 507 cm^{-1}. HRMS (ESI^+): *m*/*z* (%) = 429.1731 [M + H^+] (100). $C_{26}H_{26}N_2O_2P$ requires 429.1726.

***N*-({6-[(Diphenylphosphoryl)methyl]pyridin-2-yl}methyl)-4-methylbenzenesulfonamide (8):** To a solution of **4** (320 mg, 1.0 mmol) in water (2 mL) were added sodium hydroxide (60 mg, 1.5 mmol) and a solution of *p*-toluenesulfonyl chloride (191 mg, 1.00 mmol) in Et_2O (2 mL). The biphasic mixture was stirred in a capped vial (23 °C, 18 h) and then evaporated to dryness. The residue was dissolved in CH_2Cl_2 (2 mL), and Et_2O (10 mL) was added. Trituration and filtration afforded **8**, yield 257 mg (54%); white solid; m.p. 92–94 °C. $^{31}P\{^1H\}$ NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 29.9 ppm. ^1H NMR (300 MHz, $CDCl_3$, 298 K): δ = 7.77 (dd, $J_{H,H}$ = 11.7, 8.1 Hz, 4 H, H-9), 7.63–7.58 (m, 3 H, H-5,13), 7.51–7.39 (m, 7 H, H-4,10,11), 7.14–7.11 (m, 3 H, H-3,14), 6.57 (br. s, 1 H, NH), 4.13 (d, $J_{H,H}$ = 5.4 Hz, 2 H, H-1), 4.06 (d, $J_{H,P}$ = 13.8 Hz, 2 H, H-7), 2.33 (s, 3 H, H-16) ppm. ^{13}C NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 154.0 (C-2), 150.9 (d, $J_{C,P}$ = 6.3 Hz, C-6), 143.4 (C-12), 136.7 (C-15), 132.4 (C-11), 131.3 (d, $J_{C,P}$ = 101.7 Hz, C-8), 131.1 (d, $J_{C,P}$ = 9.6 Hz, C-9), 129.6 (C-14), 128.8 (d, $J_{C,P}$ = 12.4 Hz, C-10), 127.1 (C-13), 126.0 (C-4), 125.1 (C-5), 121.7 (C-3), 45.5 (C-1), 38.3 (d, $J_{C,P}$ = 62.7 Hz, C-7), 21.5 (C-16) ppm. FTIR (KBr): $\tilde{\nu}$ = 3049, 2872, 1595, 1566, 1487, 1461, 1439, 1407, 1349, 1330, 1288, 1262, 1246, 1177 ($\nu_{P=O}$), 1162, 1122, 1105, 1090, 1072, 996, 933, 918, 851, 817, 785, 767, 722, 712, 693, 658, 598, 577, 551, 537, 517, 499, 460 cm^{-1}. HRMS (ESI^+): *m*/*z* (%) = 477.1407 [M + H^+] (22), $C_{26}H_{26}N_2O_3PS$ requires 477.1396; 499.1231 [M + Na^+] (100), $C_{26}H_{25}N_2NaO_3PS$ requires 499.1216; 515.0974 [M + K^+] (14), $C_{26}H_{25}KN_2O_3PS$ requires 515.0955; 975.2549 [2M + Na^+] (11), $C_{52}H_{50}N_4NaO_6P_2S_2$ requires 975.2539.

***N*-({6-[(Diphenylphosphoryl)methyl]pyridin-2-yl}methyl)-4-methylbenzenesulfonamide (9):** To a solution of **5** (338 mg, 1.00 mmol) in water (2 mL) were added sodium hydroxide (60 mg, 1.5 mmol) and a solution of *p*-toluenesulfonyl chloride (229 mg, 1.20 mmol) in Et_2O (2 mL). The biphasic mixture was stirred in a capped vial (23 °C, 18 h) and was then evaporated to dryness. The residue was dissolved in CH_2Cl_2 (2 mL), and Et_2O (10 mL) was added. Trituration and filtration afforded **9**, yield 257 mg (52%); white solid; m.p. 136–138 °C. $^{31}P\{^1H\}$ NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 31.2 ppm. ^1H NMR (300 MHz, $CDCl_3$, 298 K): δ = 7.82–7.76 (m, 4 H, H-9), 7.66–7.59 (m, 1 H, H-5), 7.51–7.43 (m, 8 H, NH and H-3,10,11), 7.10–7.07 (m, 2 H, H-13), 6.95–6.94 (m, 2 H, H-14), 6.59–6.52 (m, 1 H, H-4), 4.13 (d, $J_{H,P}$ = 14.1 Hz, 2 H, H-7), 4.13–4.09 (m, 2 H, H-1), 2.32 (s, 3 H, H-16) ppm. ^{13}C NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 146.2 (C-2), 144.1 (d, $J_{C,P}$ = 6.6 Hz, C-6), 143.4 (C-12), 137.1 (C-15), 132.5 (C-11), 131.8 (d, $J_{C,P}$ = 98.0 Hz, C-8), 130.9 (d, $J_{C,P}$ = 9.9 Hz, C-9), 129.6 (C-14), 128.7 (d, $J_{C,P}$ = 12.1 Hz, C-10), 126.9 (C-13), 126.8 (C-4), 125.3 (C-5), 124.1 (C-3), 44.2 (C-1), 31.2 (d, $J_{C,P}$ = 65.7 Hz, C-7), 21.5 (C-16) ppm. FTIR (KBr): $\tilde{\nu}$ = 3420, 3059, 1597, 1567, 1492, 1438, 1416, 1379, 1329, 1289, 1245 (ν_{N-O}), 1183 ($\nu_{P=O}$), 1158, 1120, 1094, 1071, 1032, 1011, 998, 942, 853, 816, 780, 749, 721, 710, 696, 661, 604, 552, 525, 509 cm^{-1}. HRMS (ESI^+): *m*/*z* (%) = 493.1360 [M + H^+] (62), $C_{26}H_{26}N_2O_4PS$ requires 493.1345; 515.1172 [M + Na^+] (100), $C_{26}H_{25}N_2NaO_4PS$ requires 515.1165; 531.0897 [M + K^+] (22), $C_{26}H_{25}KN_2O_4PS$ requires 531.0904. $C_{26}H_{25}N_2O_4PS$ (492.53): calcd. C 63.40, H 5.12, N 5.69; found C 62.93, H 5.64, N 5.12.

***N*-({6-[(Diphenylphosphoryl)methyl]pyridin-2-yl}methyl)formamide (10):** A sample of **4** (322 mg, 1.00 mmol), triethylamine (0.28 mL, 2.0 mmol) and excess methyl formate (5.9 mL) were combined in a Schlenk flask, and the mixture was stirred (50–55 °C, 12 h). The resulting reaction mixture was evaporated to dryness, the residue was dissolved in chloroform (20 mL) and the solution was extracted with a saturated aqueous solution of ammonium chloride (20 mL). The layers were separated, and the aqueous layer was extracted with chloroform (3 × 15 mL). The combined organic layers were washed with brine (15 mL), dried ($MgSO_4$), filtered, and concentrated under reduced pressure to give **10**, yield 242 mg (69%); white solid; m.p. 110–112 °C. X-ray quality single crystals were obtained by slow evaporation of a MeOH solution (23 °C). $^{31}P\{^1H\}$ NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 31.0 ppm. ^1H NMR (300 MHz, $CDCl_3$, 298 K): δ = 7.97 (s, 1 H, H-12), 7.67–7.60 (m, 4 H, H-9), 7.39–7.29 (m, 7 H, H-4,10,11), 7.06 (d, $J_{H,H}$ = 7.8 Hz, 1 H, H-5), 6.98 (br. s, 1 H, NH), 6.87 (d, $J_{H,H}$ = 7.8 Hz, 1 H, H-3), 4.24 (d, $J_{H,H}$ = 5.1 Hz, 2 H, H-1), 3.78 (d, $J_{H,P}$ = 13.8 Hz, 2 H, H-7) ppm. ^{13}C NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 161.0 (C-12), 155.3 (C-2), 151.6 (d, $J_{C,P}$ = 7.9 Hz, C-6), 137.0 (C-4), 132.2 (d, $J_{C,P}$ = 100.5 Hz, C-8), 131.7 (d, $J_{C,P}$ = 2.0 Hz, C-11), 130.9 (d, $J_{C,P}$ = 9.4 Hz, C-9), 128.3 (d, $J_{C,P}$ = 11.8 Hz, C-10), 123.3 (d, $J_{C,P}$ = 4.0 Hz, C-5), 119.5 (C-3), 42.5 (C-1), 40.2 (d, $J_{C,P}$ = 65.0 Hz, C-7) ppm. FTIR (KBr): $\tilde{\nu}$ = 3443, 3284, 1672 (ν_{CO}), 1591, 1574, 1536, 1456, 1437, 1391, 1176 ($\nu_{P=O}$), 1120, 1104, 830, 745, 718, 694, 616, 541, 521 cm^{-1}. HRMS (ESI^+): *m*/*z* (%) = 351.1275 [M + H^+] (19), $C_{20}H_{20}N_2O_2P$ requires 351.1257; 373.1085 [M + Na^+] (100), $C_{20}H_{19}N_2NaO_2P$ requires 373.1076; 389.0819 [M + K^+] (6), $C_{20}H_{19}KN_2O_2P$ requires 389.0816.

2-[(Diphenylphosphoryl)methyl]-6-(formamidomethyl)pyridine 1-Oxide (11): A sample of **5** (500 mg, 1.48 mmol), triethylamine (0.42 mL, 3.0 mmol) and excess methyl formate (10 mL) were combined in a Schlenk vessel, and the mixture was heated and stirred (50–55 °C, 12 h). A white precipitate formed that was collected by filtration and rinsed with Et_2O (5 mL). The solid was dried under reduced pressure, and purified by column chromatography on silica gel (CH_2Cl_2/MeOH, 100:0 to 95:5) to give **11**, yield 355 mg (65%); white solid; m.p. 208–210 °C. X-ray quality single crystals were obtained by slow evaporation of a MeOH solution (23 °C). $^{31}P\{^1H\}$ NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 30.5 ppm. ^1H NMR (300 MHz, $CDCl_3$, 298 K): δ = 8.06 (s, 1 H, H-12), 7.82–7.75 (m, 4 H, H-10), 7.69–7.65 (m, 1 H, H-5), 7.52–7.38 (m, 6 H, H-9,11),

7.22–7.20 (m, 1 H, H-3), 6.98 (t, $J_{H,H}$ = 7.8 Hz, 1 H, H-4), 6.92 (br. s, 1 H, NH), 4.46 (d, $J_{H,H}$ = 6.3 Hz, 2 H, H-1), 4.21 (d, $J_{H,P}$ = 13.8 Hz, 2 H, H-7) ppm. ^{13}C NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 161.1 (C-12), 146.8 (C-2), 144.2 (d, $J_{C,P}$ = 6.5 Hz, C-6), 132.2 (d, $J_{C,P}$ = 2.0 Hz, C-11), 131.9 (d, $J_{C,P}$ = 101.8 Hz, C-8), 131.1 (d, $J_{C,P}$ = 9.8 Hz, C-9), 128.6 (d, $J_{C,P}$ = 12.1 Hz, C-10), 127.0 (d, $J_{C,P}$ = 4.2 Hz, C-5), 125.6 (C-4), 124.6 (C-3), 38.5 (C-1), 32.0 (d, $J_{C,P}$ = 65.2 Hz, C-7) ppm. FTIR (KBr): $\tilde{\nu}$ = 3426, 3232, 3032, 1678, 1590, 1562, 1541, 1484, 1436, 1414, 1395, 1377, 1340, 1263, 1242 (ν_{N-O}), 1229, 1173 ($\nu_{P=O}$), 1121, 1104, 1081, 1068, 1032, 998, 982, 952, 910, 849, 817, 795, 765, 741, 711, 694, 669, 617, 598, 558, 516, 464, 429 cm^{-1}. HRMS (ESI$^+$): *m*/*z* (%) = 367.1219 [M + H$^+$] (48) $C_{20}H_{20}N_2O_3P$ requires 367.1206; 389.1038 [M + Na$^+$] (100), $C_{20}H_{19}N_2NaO_3P$ requires 389.1026; 405.0765 [M + K$^+$] (11), $C_{20}H_{19}KN_2O_3P$ requires 405.0765; 755.2161 [2M + Na$^+$] (28), $C_{40}H_{38}N_4NaO_6P_2$ requires 755.2159. $C_{20}H_{19}N_2O_3P$ (366.35): calcd. C 65.57, H 5.23, N 7.65; found C 65.02, H 5.17, N 7.54.

***N*-({6-[(Diphenylphosphoryl)methyl]pyridin-2-yl}methyl)acetamide (12):** To a solution of **4** (322 mg, 1.00 mmol) in chloroform (5 mL, 0 °C) was added acetic anhydride (0.11 mL, 1.2 mmol). The resulting deep-red solution was stirred (23 °C, 16 h) and then washed with saturated aqueous ammonium chloride (25 mL). The aqueous layer was extracted with chloroform (3× 20 mL), and the combined organic layers were washed with brine (15 mL), dried ($MgSO_4$), filtered, and concentrated under reduced pressure. The residue was purified by column chromatography on silica gel (CH_2Cl_2/MeOH, 95:5) to give **12** as an orange oil, yield 185 mg (51%). ^{31}P{^{1}H} NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 31.0 ppm. ^{1}H NMR (300 MHz, $CDCl_3$, 298 K): δ = 7.68–7.61 (m, 4 H, H-9), 7.41–7.30 (m, 7 H, H-4,10,11), 7.10 (d, $J_{H,H}$ = 7.5 Hz, 1 H, H-5), 6.92 (d, $J_{H,H}$ = 7.5 Hz, 1 H, H-3), 6.81 (br. s, 1 H, NH), 4.26 (d, $J_{H,H}$ = 1.3 Hz, 2 H, H-1), 3.82 (d, $J_{H,P}$ = 14.4 Hz, 2 H, H-7), 1.87 (s, 3 H, H-13) ppm. ^{13}C NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 170.0 (C-12), 156.0 (C-2), 151.7 (d, $J_{C,P}$ = 7.8 Hz, C-6), 137.0 (C-4), 132.2 (d, $J_{C,P}$ = 100.4 Hz, C-8), 131.8 (C-11), 131.0 (d, $J_{C,P}$ = 9.3 Hz, C-9), 128.4 (d, $J_{C,P}$ = 11.8 Hz, C-10), 123.3 (d, $J_{C,P}$ = 3.9 Hz, C-3), 119.8 (C-5), 44.2 (C-1), 40.4 (d, $J_{C,P}$ = 64.8 Hz, C-7), 23.0 (C-13) ppm. FTIR (KBr): $\tilde{\nu}$ = 3262, 3057, 1666 ($\nu_{C=O}$), 1591, 1574, 1485, 1454, 1437, 1370, 1285, 1189 ($\nu_{P=O}$), 1120, 1070, 1027, 995, 923, 831, 720, 694, 643, 606, 521 cm^{-1}. HRMS (ESI$^+$): *m*/*z* (%) = 365.1414 [M + H$^+$] (51), $C_{21}H_{22}N_2O_2P$ requires 365.1413; 387.1234 [M + Na$^+$] (100), $C_{21}H_{21}N_2NaO_2P$ requires 387.1233; 751.2592 [2M + Na$^+$] (16), $C_{42}H_{42}N_4NaO_4P_2$ requires 751.2573.

2-(Acetamidomethyl)-6-[(diphenylphosphoryl)methyl]pyridine 1-Oxide (13): To a solution of **12** (161 mg, 0.442 mmol) in CH_2Cl_2 (7 mL) was added *m*-chloroperoxybenzoic acid (77 wt.-%, 148 mg, 0.66 mmol). The mixture was stirred (23 °C, 12 h) and then washed with an aqueous solution of NaOH (2 M, 3× 10 mL). The organic phase was dried ($MgSO_4$), filtered, and the solvent was removed by vacuum evaporation to give **13** as an orange oil, yield 115 mg (69%). ^{31}P{^{1}H} NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 30.8 ppm. ^{1}H NMR (300 MHz, $CDCl_3$, 298 K): δ = 7.76–7.69 (m, 4 H, H-9), 7.56 (d, $J_{H,H}$ = 7.8 Hz, 1 H, H-5), 7.41–7.31 (m, 6 H, H-10,11), 7.12 (d, $J_{H,H}$ = 7.5 Hz, 1 H, H-3), 7.04–6.98 (m, 2 H, H-4 and NH), 4.35 (d, $J_{H,H}$ = 6.0 Hz, 2 H, H-1), 4.15 (d, $J_{H,P}$ = 14.1 Hz, 2 H, H-7), 1.84 (s, 3 H, H-13) ppm. ^{13}C NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 170.2 (C-12), 147.5 (C-2), 143.9 (d, $J_{C,P}$ = 6.2 Hz, C-6), 132.1 (C-11), 131.9 (d, $J_{C,P}$ = 101.6 Hz, C-8), 130.8 (d, $J_{C,P}$ = 9.8 Hz, C-9), 128.5 (d, $J_{C,P}$ = 12.1 Hz, C-10), 126.4 (d, $J_{C,P}$ = 4.1 Hz, C-5), 125.3 (C-4), 124.2 (C-3), 39.8 (C-1), 31.5 (d, $J_{C,P}$ = 65.6 Hz, C-7), 23.1 (C-13) ppm. FTIR (KBr): $\tilde{\nu}$ = 3260, 3056, 1669 ($\nu_{C=O}$), 1590, 1545, 1489, 1437, 1415, 1371, 1346, 1243 (ν_{N-O}), 1184 ($\nu_{P=O}$), 1119, 1071, 1028, 997, 922, 848, 819, 784, 724, 694, 644, 588, 519, 464 cm^{-1}. HRMS (ESI$^+$): *m*/*z* (%) = 381.1378 [M + H$^+$] (25), $C_{21}H_{22}N_2O_3P$ requires 381.1363; 403.1193 [M + Na$^+$] (100), $C_{21}H_{21}N_2NaO_3P$ requires 403.1182; 419.0917 [M + K$^+$] (14), $C_{21}H_{21}KN_2O_3P$ requires 419.0921.

(*E*)-[(6-{[(2-Hydroxy-3-methoxybenzylidene)amino]methyl}pyridin-2-yl)methyl]diphenylphosphine Oxide (14): To a solution of **4** (322 mg, 1.00 mmol) in CH_2Cl_2 (5 mL) were added PPTS (13 mg, 5 mol-%), $MgSO_4$ (361 mg, 3 mmol) and *o*-vanillin (152.2 mg, 1.00 mmol). The reaction mixture was stirred (23 °C, 12 h), and then filtered. The solvent was evaporated, and the residue was purified by flash chromatography on silica gel (CH_2Cl_2/MeOH, 98:2 to 96:4) to afford **14** as an orange oil, yield 202 mg (44%). ^{31}P{^{1}H} NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 30.6 ppm. ^{1}H NMR (300 MHz, $CDCl_3$, 298 K): δ = 8.34 (s, 1 H, H-12), 7.74–7.67 (m, 4 H, H-9), 7.49 (t, $J_{H,H}$ = 7.8 Hz, 1 H, H-4), 7.41–7.34 (m, 8 H, H-5,10,11 and OH), 7.09 (d, $J_{H,H}$ = 7.8 Hz, 1 H, H-3), 6.93–6.77 (m, 3 H, H-16,17,18), 4.70 (s, 2 H, H-1), 3.88 (d, $J_{H,P}$ = 14.1 Hz, 2 H, H-7), 3.87 (s, 3 H, H-19) ppm. ^{13}C{^{1}H} NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 166.7 (C-12), 157.3 (CH_{Ar}), 152.2 (d, $J_{C,P}$ = 7.1 Hz, C-6), 151.7 (CH_{Ar}), 148.5 (CH_{Ar}), 137.2 (CH_{Ar}), 132.3 (d, $J_{C,P}$ = 100.1 Hz, C-8), 131.8 (d, $J_{C,P}$ = 2.1 Hz, C-11), 131.2 (d, $J_{C,P}$ = 9.4 Hz, C-9), 128.4 (d, $J_{C,P}$ = 11.8 Hz, C-9), 123.5 (d, $J_{C,P}$ = 3.5 Hz, C-5), 123.1 (C-18), 119.9 (C-4), 118.6 (C-3), 118.1 (C-17), 114.2 (C-16), 56.1 (C-19), 53.5 (C-1), 40.9 (d, $J_{C,P}$ = 64.2 Hz, C-7) ppm. FTIR (KBr): $\tilde{\nu}$ = 3424, 3056, 1631 ($\nu_{C=N}$), 1590, 1574, 1457, 1437, 1317, 1254, 1192 ($\nu_{P=O}$), 1120, 1103, 1080, 996, 911, 832, 783, 734, 695, 644, 522 cm^{-1}. HRMS (ESI$^+$): *m*/*z* (%) = 457.1685 [M + H$^+$] (51), $C_{27}H_{26}N_2O_3P$ requires 457.1676; 479.1491 [M + Na$^+$] (24), $C_{27}H_{25}N_2NaO_3P$ requires 479.1495.

(*E*)-2-[(Diphenylphosphoryl)methyl]-6-{[(4-hydroxy-3-methoxybenzylidene)amino]methyl}pyridine 1-Oxide (15): To a solution of **5** (338 mg, 1.00 mmol) in CH_2Cl_2 (5 mL) were added PPTS (13 mg, 5 mol-%), $MgSO_4$ (361 mg, 3 mmol) and vanillin (167.4 mg, 1.1 mmol). The reaction mixture was stirred (23 °C, 12 h), filtered, and the solvent was evaporated. The residue was purified by flash chromatography on silica gel (CH_2Cl_2/MeOH, 100:0 to 96:4) to afford **15** as an orange foam, yield 267 mg (56%). ^{31}P{^{1}H} NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 32.8 ppm. ^{1}H NMR (300 MHz, $CDCl_3$, 298 K): δ = 8.29 (s, 1 H, H-12), 7.89–7.84 (m, 4 H, H-9), 7.82–7.74 (m, 1 H, H-5), 7.46–7.43 (m, 9 H, H-10,11,14,17,18), 7.17–7.15 (m, 1 H, H-4), 6.96 (d, $J_{H,H}$ = 8.1 Hz, 1 H, H-3), 4.82 (s, 2 H, H-1), 4.30 (d, $J_{H,P}$ = 13.8 Hz, 2 H, H-7), 3.91 (s, 3 H, H-19) ppm. ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, 298 K): δ = 164.6 (C-12), 150.5 (C-2), 149.8 (C-15), 147.8 (C-13), 143.4 (d, $J_{C,P}$ = 5.9 Hz, C-6), 132.1 (C-11), 131.7 (d, $J_{C,P}$ = 100.1 Hz, C-8), 130.8 (d, $J_{C,P}$ = 9.5 Hz, C-9), 128.5 (d, $J_{C,P}$ = 11.9 Hz, C-10), 127.9 (C-16), 125.3 (C-5), 124.2 (C-4), 124.2 (C-18), 122.9 (C-17), 114.9 (C-3), 108.9 (C-14), 59.1 (C-1), 55.8 (C-19), 31.4 (d, $J_{C,P}$ = 66.3 Hz, C-7) ppm. FTIR (KBr): $\tilde{\nu}$ = 3055, 1676 ($\nu_{C=N}$), 1643, 1591, 1514, 1487, 1437, 1407, 1287, 1263, 1246 (ν_{N-O}), 1175 ($\nu_{P=O}$), 1158, 1129, 997, 851, 820, 784, 721, 695, 554, 517 cm^{-1}. HRMS (ESI$^+$): *m*/*z* (%) = 473.1620 [M + H$^+$] (40), $C_{27}H_{26}N_2O_4P$ requires 473.1625; 495.1432 [M + Na$^+$] (17), $C_{27}H_{25}N_2NaO_4P$ requires 495.1444.

(*E*)-2-[(Benzylideneamino)methyl]-6-[(diphenylphosphoryl)methyl]-pyridine 1-Oxide (16): To a solution of **5** (100 mg, 0.30 mmol) in CH_2Cl_2 (5 mL) were added molecular sieves (4 Å) (150 mg) and benzaldehyde (0.03 mL, 0.3 mmol). The reaction mixture was stirred (23 °C, 14 h), filtered, and the solvent was evaporated. The residue was purified by flash chromatography on silica gel (CH_2Cl_2/MeOH, 100:0 to 98:2) to afford **16**, yield 80.0 mg (63%); off-yellow solid; m.p.174–176 °C. X-ray quality single crystals were obtained by slow evaporation of a MeOH/CH_2Cl_2 solution (23 °C). ^{31}P{^{1}H}

NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 32.5 ppm. ^1H NMR (300 MHz, $CDCl_3$, 298 K): δ = 8.43 (s, 1 H, H-12), 7.88–7.78 (m, 6 H, H-9,14), 7.71 (d, $J_{H,H}$ = 7.8 Hz, 1 H, H-5), 7.48–7.36 (m, 9 H, H-10,11,15,16), 7.35–7.32 (m, 1 H, H-3), 7.14 (t, $J_{H,H}$ = 7.8 Hz, 1 H, H-4), 4.85 (s, 2 H, H-1), 4.29 (d, $J_{H,P}$ = 14.1 Hz, 2 H, H-7) ppm. $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$, 298 K): δ = 164.7 (C-12), 150.2 (C-2), 143.6 (d, $J_{C,P}$ = 5.6 Hz, C-6), 135.9 (C-13), 132.2 (d, $J_{C,P}$ = 101.5 Hz, C-8), 132.1 (d, $J_{C,P}$ = 1.9 Hz, C-11), 131.5 (C-16), 131.0 (d, $J_{C,P}$ = 9.9 Hz, C-9), 128.7 (d, $J_{C,P}$ = 10.0 Hz, C-10), 128.5 (C-14 or C-16), 128.4 (C-14 or C-16), 125.4 (d, $J_{C,P}$ = 4.2 Hz, C-3), 125.0 (C-4), 122.9 (C-5), 59.3 (C-1), 31.5 (d, $J_{C,P}$ = 66.4 Hz, C-7) ppm. FTIR (KBr): $\tilde{\nu}$ = 2958, 2870, 1695 ($\nu_{C=N}$), 1646, 1581, 1563, 1482, 1458, 1439, 1424, 1397, 1332, 1312, 1245, 1223, 1191 ($\nu_{P=O}$), 1118, 1108, 1069, 1048, 1026, 1000, 974, 924, 909, 846, 822, 696, 606, 574, 514 cm^{-1}. HRMS (ESI^+): *m*/*z* (%) = 427.1581 [M + H^+] (49), $C_{26}H_{24}N_2O_2P$ requires 427.1575; 449.1398 [M + Na^+] (100), $C_{26}H_{23}N_2NaO_2P$ requires 449.1395; 875.2862 [2M + Na^+] (80), $C_{52}H_{46}N_4NaO_4P_2$ requires 875.2892.

(*E*)-*N*′-({6-[(Diphenylphosphoryl)methyl]pyridin-2-yl}methyl)-*N*,*N*-dimethylacetimidamide (17): To a mixture of **4** (322 mg, 1.00 mmol) and dimethylamine (2 M in THF, 1.2 mL, 2.4 mmol) in THF (2 mL) were added dropwise, under nitrogen, with stirring (23 °C), *N*,*N*-dimethylacetamide dimethyl acetal (90%, 0.2 mL, 1.2 mmol). The mixture was stirred (10 min) and then left under nitrogen in the dark without stirring (23 °C, 18 h). Evaporation of the volatiles afforded **17** as an orange oil that solidified upon standing, yield 369 mg (94%). $^{31}P\{^1H\}$ NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 30.4 ppm. ^1H NMR (300 MHz, $CDCl_3$, 298 K): δ = 7.68–7.62 (m, 4 H, H-9), 7.39 (t, $J_{H,H}$ = 7.8 Hz, 1 H, H-4), 7.35–7.24 (m, 6 H, H-10,11), 7.21 (d, $J_{H,H}$ = 7.8 Hz, 1 H, H-5), 7.16 (d, $J_{H,H}$ = 7.5 Hz, 1 H, H-3), 4.33 (s, 2 H, H-1), 3.81 (d, $J_{H,P}$ = 14.1 Hz, 2 H, H-7), 2.82 (s, 6 H, H-14), 1.71 (s, 3 H, H-13) ppm. $^{13}C\{^1H\}$ NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 162.1 (C-12), 160.1 (C-2), 150.8 (d, $J_{C,P}$ = 6.9 Hz, C-6), 136.5 (C-4), 132.2 (d, $J_{C,P}$ = 100.2 Hz, C-8), 131.4 (C-11), 130.8 (d, $J_{C,P}$ = 9.3 Hz, C-9), 128.1 (d, $J_{C,P}$ = 11.8 Hz, C-10), 122.0 (d, $J_{C,P}$ = 3.1 Hz, C-5), 118.9 (C-3), 55.1 (C-1), 40.6 (d, $J_{C,P}$ = 64.6 Hz, C-7), 37.8 (C-14), 12.8 (C-13) ppm. FTIR (KBr): $\tilde{\nu}$ = 3206, 2925, 2854, 1676 ($\nu_{C=N}$), 1591, 1561, 1459, 1438, 1379, 1315, 1178 ($\nu_{P=O}$), 1124, 1099, 1071, 997, 885, 847, 800, 747, 722, 694, 633, 508 cm^{-1}. HRMS (ESI^+): *m*/*z* (%) = 392.1897 [M + H^+] (100), $C_{23}H_{27}N_3OP$ requires 392.1886.

2-({6-[(Diphenylphosphoryl)methyl]pyridin-2-yl}methyl)-1,1,3,3-tetramethylguanidine (18): Oxalyl chloride (4.3 mL, 6.4 mmol) was added dropwise to a solution of tetramethylurea (1.21 mL, 10.1 mmol) in chloroform (8 mL). The resulting solution was stirred (105 °C, 18 h) under nitrogen and evaporation of the volatiles afforded tetramethylchloroformamidinium chloride (1.72 g, 10.1 mmol, 100%). Triethylamine (0.80 mL, 5.7 mmol) was added to a solution of **4** (841 mg, 2.6 mmol) in CH_2Cl_2 (13 mL) followed by slow addition of a solution of tetramethylchloroformamidinium chloride (578 mg, 3.38 mmol) in CH_2Cl_2 (6 mL, –10 °C). The reaction mixture was stirred (–10 °C, 1 h), then 10% aqueous HCl (10 mL) solution was added. The phases were separated, and the organic layer was washed with 10% HCl (2× 10 mL). The combined aqueous layers were washed with CH_2Cl_2 (10 mL) and then 50% KOH (20 mL) was added. The aqueous layer was extracted with toluene (2× 20 mL), the combined organic layers were dried (K_2CO_3), filtered, and concentrated under reduced pressure to afford **18**, yield 855 mg (78%); yellow solid; m.p. 116–118 °C. X-ray quality single crystals were obtained by slow evaporation of a MeOH solution (23 °C). $^{31}P\{^1H\}$ NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 30.4 ppm. ^1H NMR (300 MHz, $CDCl_3$, 298 K): δ = 7.71–7.64 (m, 4 H, H-9), 7.46–7.27 (m, 8 H, H-4,5,10,11), 7.17 (d, $J_{H,H}$ = 7.5 Hz, 1 H, H-3), 4.30 (s, 2 H, H-1), 3.84 (d, $J_{H,P}$ = 14.4 Hz, 2 H, H-7), 2.66 (s, 6 H, H-13), 2.65 (s, 6 H, H-13) ppm. $^{13}C\{^1H\}$ NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 163.3 (C-12), 161.2 (C-2), 150.8 (d, $J_{C,P}$ = 6.8 Hz, C-6), 136.7 (C-4), 132.5 (d, $J_{C,P}$ = 100.1 Hz, C-8), 131.6 (d, $J_{C,P}$ = 2.0 Hz, C-11), 131.1 (d, $J_{C,P}$ = 9.3 Hz, C-9), 128.3 (d, $J_{C,P}$ = 11.8 Hz, C-10), 122.1 (d, $J_{C,P}$ = 3.2 Hz, C-5), 119.1 (C-3), 54.9 (C-1), 40.9 (d, $J_{C,P}$ = 64.9 Hz, C-7), 39.6 (C-13), 38.9 (C-13) ppm. FTIR (KBr): $\tilde{\nu}$ = 3053, 1612 ($\nu_{C=O}$), 1588, 1574, 1500, 1454, 1436, 1420, 1402, 1370, 1339, 1267, 1234, 1188 ($\nu_{P=O}$), 1132, 1115, 1066, 1026, 1008, 908, 826, 804, 743, 716, 699, 547, 519, 497 cm^{-1}. HRMS (ESI^+): *m*/*z* (%) = 421.2145 [M + H^+] (100), $C_{24}H_{30}N_4OP$ requires 421.2152. $C_{24}H_{29}N_4OP$ (420.49): calcd. C 68.55, H 6.95, N 13.32; found C 67.95, H 7.02, N 13.06.

2-({[Bis(dimethylamino)methylene]amino}methyl)-6-[(diphenylphosphoryl)methyl]pyridine 1-Oxide (19): Oxalyl chloride (2.2 mL, 26.2 mmol) was added dropwise, under nitrogen, to a solution of tetramethylurea (0.64 mL, 5.3 mmol) in chloroform (8 mL, 23 °C). The resulting solution was stirred (105 °C, 18 h) and then evaporated providing tetramethylchloroformamidinium chloride (912 mg, 5.33 mmol, 100%). Triethylamine (0.46 mL, 3.3 mmol) was added to a solution of **5** (508 mg, 1.50 mmol) in CH_2Cl_2 (15 mL) followed by slow addition of a solution of tetramethylchloroformamidinium chloride (334 mg, 1.95 mmol) in CH_2Cl_2 (5 mL, –10 °C). The reaction mixture was stirred (–10 °C, 1 h) then 10% aqueous HCl (15 mL) solution was added. The phases were separated, and the organic layer was washed with 10% HCl (2× 15 mL). The combined aqueous layers were washed with CH_2Cl_2 (15 mL), and then aqueous NaOH (3 M, 30 mL) was added. The aqueous layer was extracted with benzene (2× 25 mL), and the combined organic layers were dried (K_2CO_3), filtered, and concentrated under reduced pressure to give **19** as an orange oil, yield 458 mg (70%). X-ray quality single crystals were obtained by slow evaporation of a MeOH solution (23 °C). $^{31}P\{^1H\}$ NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 32.6 ppm. ^1H NMR (300 MHz, $CDCl_3$, 298 K): δ = 7.77–7.71 (m, 4 H, H-9), 7.59–7.54 (m, 2 H, H-3,5), 7.34–7.26 (m, 6 H, H-10,11), 7.04 (t, $J_{H,H}$ = 8.0 Hz, 1 H, H-4), 4.35 (s, 2 H, H-1), 3.84 (d, $J_{H,P}$ = 13.8 Hz, 2 H, H-7), 2.69 (s, 6 H, H-13), 2.64 (s, 6 H, H-13) ppm. $^{13}C\{^1H\}$ NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 161.9 (C-12), 153.6 (C-2), 142.8 (d, $J_{C,P}$ = 5.0 Hz, C-6), 132.1 (d, $J_{C,P}$ = 101.5 Hz, C-8), 131.8 (d, $J_{C,P}$ = 1.7 Hz, C-11), 130.7 (d, $J_{C,P}$ = 9.8 Hz, C-9), 128.4 (d, $J_{C,P}$ = 12.1 Hz, C-10), 124.9 (C-4), 124.1 (d, $J_{C,P}$ = 3.9 Hz, C-5), 122.4 (C-3), 48.5 (C-1), 39.5 (C-13), 38.8 (C-13), 30.9 (d, $J_{C,P}$ = 67.0 Hz, C-7) ppm. FTIR (KBr): $\tilde{\nu}$ = 3440, 3054, 1620 ($\nu_{C=N}$), 1603, 1490, 1437, 1401, 1372, 1313, 1238 (ν_{N-O}), 1185 ($\nu_{P=O}$), 1118, 1059, 1009, 941, 908, 848, 819, 786, 720, 695, 593, 517 cm^{-1}. HRMS (ESI^+): *m*/*z* (%) = 437.2108 [M + H^+] (100) $C_{24}H_{30}N_4O_2P$ requires 437.2101.

[(6-{[1*H*-Naphtho[1,2-*e*][1,3]oxazin-2(3*H*)-yl]methyl}pyridin-2-yl)-methyl]diphenylphosphine Oxide (20): To a solution of **4** (323 mg, 1.00 mmol) in THF (1 mL) and water (2 mL) was added formaldehyde (37%, 0.80 mL). The mixture was stirred (5 min, 23 °C) and 2-naphthol (144 mg, 1.00 mmol) was added. The resulting mixture was stirred (16 h, 23 °C), and the solvent was evaporated. The residue was purified by flash chromatography on silica gel (CH_2Cl_2/MeOH: 98:2) to afford **20** as an orange oil, yield 202 mg (41%). $^{31}P\{^1H\}$ NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 29.7 ppm. ^1H NMR (300 MHz, $CDCl_3$, 298 K): δ = 7.77–7.70 (m, 5 H, H-6,21), 7.64 (d, $J_{H,H}$ = 8.7 Hz, 1 H, H-4), 7.55 (t, $J_{H,H}$ = 7.8 Hz, 1 H, H-16), 7.43–7.41 (m, 3 H, H-8,9,17), 7.34–7.29 (m, 7 H, H-7,22,23), 7.22 (d, $J_{H,H}$ = 7.8 Hz, 1 H, H-15), 7.05 (d, $J_{H,H}$ = 9.0 Hz, 1 H, H-3), 4.81 (s, 2 H, H-12), 4.19 (s, 2 H, H-13), 3.93 (d, $J_{H,P}$ = 14.4 Hz, 2 H, H-19), 3.93 (s, 2 H, H-11) ppm. $^{13}C\{^1H\}$ NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 157.9 (C-2), 152.2 (d, $J_{C,P}$ = 7.0 Hz, C-18),

151.7 (C-14), 137.0 (C-16), 132.4 (d, $J_{C,P}$ = 100.2 Hz, C-20), 131.9 (C-5), 131.7 (C-23), 131.1 (d, $J_{C,P}$ = 9.4 Hz, C-21), 129.0 (C-10), 128.6 (C-6), 128.4 (d, $J_{C,P}$ = 11.9 Hz, C-22), 128.0 (C-4), 126.5 (C-8), 123.6 (d, $J_{C,P}$ = 3.4 Hz, C-17), 123.5 (C-7), 121.1 (C-9,15), 118.6 (C-3), 82.3 (C-12), 57.7 (C-11), 47.6 (C-13), 40.8 (d, $J_{C,P}$ = 64.0 Hz, C-19) ppm. FTIR (KBr): $\tilde{\nu}$ = 3055, 1667, 1623, 1590, 1574, 1513, 1470, 1455, 1436, 1399, 1353, 1310, 1265, 1227, 1186 ($\nu_{P=O}$), 1121, 1061, 1027, 994, 958, 931, 902, 865, 813, 771, 747, 717, 694, 521 cm^{-1}. HRMS (ESI^+): *m*/*z* (%) = 491.1895 [M + H^+] (100), $C_{31}H_{28}N_2O_2P$ requires 491.1883; 513.1714 [M + Na^+] (85) $C_{31}H_{27}N_2NaO_2P$ requires 513.1702; 981.3720 [2M + H^+] (46), $C_{62}H_{55}N_4O_4P_2$ requires 981.3693.

2-{[1*H*-Naphtho[1,2-*e*][1,3]oxazin-2(3*H*)-yl]methyl}-6-[(diphenylphosphoryl)methyl]pyridine 1-Oxide (21): A solution of **5** (338 mg, 1.00 mmol) and formaldehyde (37%, 0.20 mL) was stirred (30 min, 23 °C) and recrystallized 2-naphthol (111 mg, 0.77 mmol) was added. The orange solution was stirred (3 h, 80 °C) and then cooled (23 °C). The residue was dissolved in CH_2Cl_2 (20 mL), dried with $MgSO_4$, filtered, and the solvent evaporated. Purification on silica gel (CH_2Cl_2/MeOH, 98:2) afforded a **21** as a yellow powder, yield 313 mg (80%); m.p. 114–116 °C. Crystals were obtained by slow evaporation of a CH_2Cl_2 solution. $^{31}P\{^1H\}$ NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 31.7 ppm. ^1H NMR (300 MHz, $CDCl_3$, 298 K): δ = 7.82–7.75 (m, 4 H, H-21), 7.72 (d, $J_{H,H}$ = 6.1 Hz, 1 H, H-9), 7.66–7.64 (m, 1 H, H-17), 7.61 (d, $J_{H,H}$ = 9.0 Hz, 1 H, H-4), 7.47–7.37 (m, 3 H, H-6,7,8), 7.33–7.26 (m, 7 H, H-15,22,23), 7.14 (t, $J_{H,H}$ = 7.8 Hz, 1 H, H-16), 7.03 (d, $J_{H,H}$ = 9.0 Hz, 1 H, H-3), 4.87 (s, 2 H, H-12), 4.20 (d, $J_{H,P}$ = 14.1 Hz, 2 H, H-19), 4.19 (s, 2 H, H-11), 4.02 (s, 2 H, H-13) ppm. $^{13}C\{^1H\}$ NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 151.6 (C-2), 149.1 (C-14), 144.1 (d, $J_{C,P}$ = 6.3 Hz, C-18), 131.8 (d, $J_{C,P}$ = 1.9 Hz, C-23), 131.7 (d, $J_{C,P}$ = 101.4 Hz, C-20), 131.7 (C-5), 130.7 (d, $J_{C,P}$ = 9.9 Hz, C-21), 128.9 (C-10), 128.6 (C-9), 128.2 (d, $J_{C,P}$ = 12.3 Hz, C-22), 128.1 (C-4), 126.4 (C-6 or C-8), 125.2 (d, $J_{C,P}$ = 3.9 Hz, C-17), 124.6 (C-16), 123.4 (C-6 or C-8), 122.8 (C-15), 120.7 (C-7), 118.5 (C-3), 111.1 (C-1), 82.7 (C-12), 51.5 (C-13), 48.2 (C-11), 31.9 (d, $J_{C,P}$ = 65.7 Hz, C-19) ppm. FTIR (KBr): $\tilde{\nu}$ = 3057, 1896, 1673, 1624, 1597, 1571, 1514, 1474, 1436, 1409, 1386, 1357, 1305, 1263, 1228, 1206, 1170 ($\nu_{P=O}$), 1119, 1066, 1047, 1027, 998, 963, 941, 898, 842, 771, 742, 718, 695, 602, 524, 506 cm^{-1}. HRMS (ESI^+): *m*/*z* (%) = 507.1850 [M + H^+] (9), $C_{31}H_{28}N_2O_3P$ requires 507.1832; 529.1651 [M + Na^+] (100), $C_{31}H_{27}N_2NaO_3P$ requires 529.1652.

6,6′-[Naphtho[1,2-*e*:5,6-*e*′]bis([1,3]oxazine)-3,9(2*H*,4*H*,8*H*,10*H*)-diylbis(methylene)]bis{2-[(diphenylphosphoryl)methyl]pyridine 1-Oxide} (22): A solution of **5** (338 mg, 1.00 mmol) and formaldehyde (37%, 0.20 mL) was stirred (30 min) and recrystallized 1,5-dihydroxynaphthalene (61.70 mg, 0.385 mmol) was added. The clear yellow solution was stirred (3 h, 80 °C) and then cooled (23 °C). The residue was dissolved in CH_2Cl_2 (20 mL), dried with $MgSO_4$, filtered, and the solvent was evaporated. Purification on silica gel (CH_2Cl_2/MeOH, 98:2) afforded **22**, yield 245 mg (72%); off-white powder; m.p.140–142 °C. $^{31}P\{^1H\}$ NMR (121.49 MHz, $CDCl_3$, 298 K): δ = 32.0 ppm. ^1H NMR (300 MHz, $CDCl_3$, 298 K): δ = 7.87–7.81 (m, 6 H, H-11,19), 7.73 (d, $J_{H,H}$ = 6.9 Hz, 2 H, H-4), 7.55–7.37 (m, 18 H, H-13,17,18), 7.23 (t, $J_{H,H}$ = 7.0 Hz, 2 H, H-12), 7.08 (d, $J_{H,H}$ = 9.0 Hz, 2 H, H-3), 4.92 (s, 4 H, H-8), 4.28 (s, 4 H, H-7), 4.26 (d, $J_{H,P}$ = 9.9 Hz, 4 H, H-15), 4.08 (s, 4 H, H-9) ppm. $^{13}C\{^1H\}$ NMR (75.4 MHz, $CDCl_3$, 298 K): δ = 150.3 (C-2), 149.3 (C-10), 144.3 (d, $J_{C,P}$ = 6.0 Hz, C-14), 132.0 (C-19), 131.8 (d, $J_{C,P}$ = 101.5 Hz, C-16), 131.0 (C-5 or C-6), 130.9 (d, $J_{C,P}$ = 9.8 Hz, C-17), 128.4 (d, $J_{C,P}$ = 12.0 Hz, C-18), 127.2 (C-5 or C-6), 125.5 (d, $J_{C,P}$ = 2.5 Hz, C-13), 124.9 (C-4 or C-11 or C-12), 123.0 (C-4 or C-11 or C-12), 121.1 (C-4 or C-11 or C-12), 118.9 (C-3), 112.6 (C-1), 82.7 (C-8), 51.7 (C-7), 48.5 (C-9), 32.0 (d, $J_{C,P}$ = 65.3 Hz, C-15) ppm. FTIR (KBr): $\tilde{\nu}$ = 3054, 1600, 1567, 1520, 1487, 1438, 1406, 1358, 1306, 1263, 1224, 1177 ($\nu_{P=O}$), 1138, 1120, 1053, 1018, 997, 922, 845, 818, 743, 722, 697, 633, 609, 518 cm^{-1}. HRMS (ESI^+): *m*/*z* (%) = 885.2976 [M + H^+] (67), $C_{52}H_{47}N_4O_6P_2$ requires 885.2965; 907.2811 [M + Na^+] (100), $C_{52}H_{46}N_4NaO_6P_2$ requires 907.2785.

Syntheses of Complexes: Coordination complexes were prepared by combination of a sample of ligand (1 equiv.), dissolved in a minimum of MeOH, with $Ln(NO_3)_3{\cdot}xH_2O$ (1 equiv.), dissolved in a minimum of MeOH. The mixtures were stirred (23 °C, 12 h), and the solvent was evaporated to give white powders. The FTIR spectra were recorded for the crude complexes and spectra for four representative recrystallized complexes are listed: [Er(**3**)$(NO_3)_3$] pink solid crystallized by slow evaporation of a MeOH/acetone solution. FTIR (KBr): $\tilde{\nu}$ = 1777, 1723 (ν_{CO}), 1213 (ν_{NO}), 1161 (ν_{PO}) cm^{-1}. [Pr(**5**)$(NO_3)_3$] FTIR (KBr): $\tilde{\nu}$ = 1222 (ν_{NO}), 1161 (ν_{PO}) cm^{-1}. [Pr(**11**)$(NO_3)_3(CH_3OH)]_2$, white solid crystallized by slow evaporation of a MeOH/CH_2Cl_2 solution. FTIR (KBr): $\tilde{\nu}$ = 1656 (ν_{CO}), 1214 (ν_{NO}), 1164 (ν_{PO}), 1141, 1121 cm^{-1}. [Eu(**18**H_2^{2+})$(NO_3)_4(OCH_3)$], white solid crystallized by slow evaporation of a MeOH/CH_3CN solution. FTIR (KBr): $\tilde{\nu}$ = 1622 (ν_{CN}), 1166 (ν_{PO}) cm^{-1}. Additional IR data for these and other complexes are provided in the Supporting Information.

X-ray Diffraction Analyses: Crystals were coated with Paratone oil and mounted on a CryoLoop attached to a metal pin with epoxy. Diffraction data were collected with a Bruker X8 Apex II CCD-based X-ray diffractometer equipped with an Oxford Cryostream 700 low-temperature device and normal focus Mo-target X-ray tube (λ = 0.71073 Å) operated at 1500 W power (50 kV, 30 mA). Data collection and processing were accomplished with the Bruker APEX2 software suite.[28] Structures were solved by direct methods and refined with full-matrix least-squares methods on F^2 with use of SHELXTL.[29] Lattice and data collection parameters for the ligands and the metal complexes are provided in Tables 1, 2, 3, and 4. Unless otherwise indicated below, all heavy atoms were refined anisotropically and C–H hydrogen atoms were included in idealized positions and refined isotropically (riding model) with U_{iso} = 1.2U_{eq} of the parent atom with the exception of terminal methyl groups (U_{iso} = 1.5U_{eq}). The N–H and O–H hydrogen atoms were located in the diffraction map and were refined with U_{iso} = 1.5U_{eq} of the parent atom. The structure refinements were well behaved except as indicated in the following notes. For **3**·1/2$(CH_3)_2CO$ there are two molecules of **3** and one acetone in the unit cell, and the acetone is disordered over two sites of equal occupancy related by a center of symmetry. The structure for the complex [Eu(**18**H_2^{2+})$(NO_3)_4(OCH_3)$] contains disordered lattice solvent molecules, likely either H_2O or MeOH or a combination, that were not adequately modeled. The refinement was improved by application of the SQUEEZE procedure,[30] and PLATON estimated 16 electrons unaccounted for in a solvent-accessible void volume of 58 $Å^3$.

CCDC-835053 (for **1**), -835054 (for **2**·MeOH), -835055 (for **3**·1/2Me_2CO), -835056 {for [Er(**3**)$(NO_3)_3$(MeOH)]}, -835057 {for [**4**H]Cl(BuOH)}, -835058 (for **11**), -835059 (for **16**) and 977951 (for **4**·H_2O), -977952 (for **10**), -977953 [for Pr_2(**11**)$_2(NO_3)_6(MeOH)_2$], -977954 (for **18**), -977955 {for [Eu(**18**H_2)$(NO_3)_4$(OMe)]}, -977956 (for **19**), -977957 (for **21**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Molecular Mechanics Calculations. Geometry optimizations of the free and Eu^{III}-bound forms of **11** were carried out with the MM3

Table 1. Crystallographic data for **1**, **2**·MeOH, **3**·1/2Me_2CO, **4**·H_2O, and [**4**H$^+$]Cl·*t*BuOH.

	1	**2**·MeOH	**3**·1/2Me_2CO	**4**·H_2O	[**4**H$^+$]Cl·*t*BuOH
Data set label	rpsl47	rpsl44	rpsl48	rpso813	rpso13
Crystal size [mm]	0.30 × 0.25 × 0.05	0.41 × 0.25 × 0.12	0.44 × 0.32 × 0.23	0.23 × 0.31 × 0.35	0.41 × 0.25 × 0.05
Empirical formula	$C_{15}H_{11}ClN_2O_2$	$C_{28}H_{25}N_2O_4P$	$C_{28.5}H_{24}N_2O_{4.5}P$	$C_{19}H_{21}N_2O_2P$	$C_{23}H_{30}ClN_2O_2P$
Formula weight	286.71	484.47	497.47	340.35	340.35
Crystal system	triclinic	triclinic	triclinic	triclinic	monoclinic
Space group	$P\bar{1}$	$P\bar{1}$	$P\bar{1}$	$P\bar{1}$	*C*2/*c*
a [Å]	5.8670(2)	7.2786(1)	10.1728(11)	5.5420(4)	27.2524(9)
b [Å]	8.1289(3)	8.6830(2)	10.5427(11)	9.0086(7)	11.6873(4)
c [Å]	13.7985(4)	20.6140(4)	12.1664(13)	9.0345(7)	16.9187(6)
α [°]	86.864(2)	81.995(1)	87.253(4)	86.4070(18)	90
β [°]	86.292(2)	88.287(1)	82.652(5)	76.6270(15)	118.3280(10)
γ [°]	81.405(2)	71.251(1)	81.586(5)	86.4280(18)	90
V [Å^3]	648.65(4)	1221.50(4)	1279.6(2)	437.43(6)	4743.4(3)
Z	2	2	2	1	8
T [K]	233(2)	228(2)	233(2)	100(2)	150(2)
D [g cm^{-3}]	1.468	1.317	1.291	1.292	1.212
μ [cm^{-1}]	0.296	0.150	0.147	0.170	0.249
Measured reflections	14368	33085	34822	5162	64225
Independent reflections	3962	10378	9816	3197	9057
R_{int}	0.0225	0.0221	0.0211	0.0204	0.0290
Final *R* indices [$I > 2\sigma(I)$][a]	0.0409	0.0460	0.0460	0.0279	0.0279
$R_1(wR_2)$	0.0947	0.1290	0.1290	0.0673	0.0673

[a] $R_1 = \Sigma||F_o| - |F_c||/\Sigma|F_o|$, $wR_2 = [\Sigma w(F_o^2 - F_c^2)_2/\Sigma wF_o^2]^{1/2}$.

Table 2. Crystallographic data for **10**·2H_2O, **11**, and **16**.

	10·2H_2O	**11**	**16**
Data set label	rpso217	rpso4	rpso11
Crystal size [mm]	0.29 × 0.42 × 0.51	0.34 × 0.09 × 0.07	0.41 × 0.28 × 0.23
Empirical formula	$C_{20}H_{23}N_2O_4P$	$C_{20}H_{19}N_2O_3P$	$C_{26}H_{23}N_2O_2P$
Formula weight	386.37	366.34	426.43
Crystal system	monoclinic	monoclinic	monoclinic
Space group	*C*2/*c*	$P2_1/n$	$P2_1/n$
a [Å]	18.4679(6)	10.4956(3)	8.5041(3)
b [Å]	7.7408(2)	13.7854(4)	16.5369(6)
c [Å]	27.6281(8)	12.0267(3)	15.3016(5)
α [°]	90	90	90
β [°]	99.315(2)	90.3560(10)	92.731(2)
γ [°]	90	90	90
V [Å^3]	3897.5(2)	1740.06(8)	2149.44(13)
Z	8	4	4
T [K]	228(2)	150(2)	150(2)
D [g cm^{-3}]	1.317	1.398	1.318
μ [cm^{-1}]	0.169	0.181	0.154
Measured reflections	25852	42324	69285
Independent reflections	4840	6999	7828
R_{int}	0.0320	0.0366	0.0270
Final *R* indices [$I > 2\sigma(I)$][a]	0.0437	0.0437	0.0432
$R_1(wR_2)$	0.1126	0.1069	0.1009

[a] $R_1 = \Sigma||F_o| - |F_c||/\Sigma|F_o|$, $wR_2 = [\Sigma w(F_o^2 - F_c^2)_2/\Sigma wF_o^2]^{1/2}$.

force field[31] using a points-on-a-sphere metal ion[32] as implemented in PCModel software.[33] Conformational searches to locate the most stable form for each structure were performed using the GMMX algorithm provided with this software. Input files required to repeat these calculations including additional parameters for treating the metal-dependent interactions, are available from an author (B. P. H.).

Supporting Information (see footnote on the first page of this article): NMR, IR and MS characterization data for **1**–**22**, IR data for the complexes, ORTEP views for **1**–**4**, [**4**H$^+$]Cl$^-$, **10**, **11**, **16**, **18**, **19**, and **21** and summary tables of selected bond lengths (155 pages).

Acknowledgments

Financial support for this study at the University of New Mexico was provided by the U. S. Department of Energy, Office of Basic Energy Sciences, Division of Chemical Sciences, Geosciences and Biosciences [grant number DE-FG02-03ER15419 (to R. T. P.)]. In

Table 3. Crystallographic data for **18**, **19**, and **21**·H_2O.

	18	**19**	**21**·H_2O
Data set label	rpso394	rpso615	rpso809f1
Crystal size [mm]	$0.30 \times 0.36 \times 0.49$	$0.15 \times 0.24 \times 0.29$	$0.13 \times 0.22 \times 0.45$
Empirical formula	$C_{24}H_{29}N_4OP$	$C_{24}H_{29}N_4O_2P$	$C_{31}H_{29}N_2O_4P$
Formula weight	420.49	436.49	524.53
Crystal system	monoclinic	orthorhombic	triclinic
Space group	$P2_1/c$	$Pbca$	$P\bar{1}$
a [Å]	13.3211(5)	14.509(2)	7.2902(3)
b [Å]	11.0381(4)	16.611 (3)	12.5149(5)
c [Å]	17.6697(6)	18.562(3)	15.4101(6)
α [°]	90	90	67.6510(11)
β [°]	118.402(2)	90	83.3020(12)
γ [°]	90	90	83.4170(12)
V [Å^3]	2285.41(14)	4473.6(12)	1287.69(9)
Z	4	8	2
T [K]	173(2)	173(2)	100(2)
D [g cm^{-3}]	1.222	1.296	1.353
μ [cm^{-1}]	0.143	0.152	0.148
Measured reflections	18805	41265	20045
Independent reflections	4712	4564	5255
R_{int}	0.0423	0.1183	0.0266
Final R indices			
$[I > 2\sigma(I)]$[a]	0.0400	0.0410	0.0348
$R_1(wR_2)$	0.0961)	0.0932)	0.0829)

[a] $R_1 = \Sigma||F_o| - |F_c||/\Sigma|F_o|$, $wR_2 = [\Sigma w(F_o^2 - F_c^2)_2/\Sigma wF_o^2]^{1/2}$.

Table 4. Crystallographic data for lanthanide complexes.

	[Er(**3**)$(NO_3)_3$(MeOH)]·(Me_2CO)	Pr_2(**11**)$_2(NO_3)_6(MeOH)_2$	{[Eu(**18**H_2^{2+})]$(NO_3)_4$(OMe)}
Data set label	rpsl46.1	rpso207	rpso399
Crystal size [mm]	$0.34 \times 0.12 \times 0.07$	$0.06 \times 0.10 \times 0.11$	$0.12 \times 0.34 \times 0.44$
Empirical formula	$C_{31}H_{31}ErN_5O_{15}P$	$C_{42}H_{46}N_{10}O_{26}P_2Pr_3$	$C_{25}H_{34}EuN_8O_{14}P$
Formula weight	911.84	1450.63	853.52
Crystal system	triclinic	triclinic	triclinic
Space group	$P\bar{1}$	$P\bar{1}$	$P\bar{1}$
a [Å]	10.8549 (4)	8.5507(7)	10.9993(4)
b [Å]	12.0304(4)	9.7696(8)	12.6232(5)
c [Å]	15.3469(5)	17.7362(16)	14.0972(6)
α [°]	68.9990(16)	78.751(6)	77.850(2)
β [°]	78.0470(15)	76.120(6)	68.677(2)
γ [°]	73.3510(15)	66.808(6)	72.641(2)
V [Å^3]	1780.31(11)	1313.70(19)	1728.82(12)
Z	2	1	2
T [K]	228(2)	173(2)	173(2)
D [g cm^{-3}]	1.701	1.834	1.640
μ [cm^{-1}]	2.479	1.992	1.935
Measured reflections	45578	12370	28146
Independent reflections	10016	5595	7811
R_{int}	0.0221	0.0768	0.0381
Final R indices			
$[I > 2\sigma(I)]$[a]	0.0220	0.0513	0.0344
$R_1(wR_2)$	0.0573	0.0768	0.0973

[a] $R_1 = \Sigma||F_o| - |F_c||/\Sigma|F_o|$, $wR_2 = [\Sigma w(F_o^2 - F_c^2)_2/\Sigma wF_o^2]^{1/2}$.

addition, funds from the National Science Foundation (NSF) assisted with the purchases of the X-ray diffractometer (CHE-0443580) and NMR spectrometers (CHE-0840523 and -0946690). Support for molecular modeling (to B. P. H.) studies at Oak Ridge National Laboratory was provided by the DOE, Office of Science, BES, Chemical Sciences, Geosciences, and Biosciences Division. The authors thank Professor G. Lynn Wood, Valdosta State University for recording DSC and TGA scans on the naphthoxazine samples.

[1] a) K. L. Nash, C. Madic, J. N. Mathur, J. Lacquement, in: *The Chemistry of the Actinide and Transactinide Elements* (Eds.: L. R. Morss, N. M. Edelstein, J. Fuger), Springer, Dordrecht, The Netherlands, **2006**, vol. 4, chapter 24, p. 2622–2798; b) C. Hill, in: *Ion Exchange and Solvent Extraction: A Series of Advances* (Ed.: B. A. Moyer) CRC, Boca Raton, FL, **2010**, vol. 19, p. 119–194; c) Z. Kolarik, *Chem. Rev.* **2008**, *108*, 4208–4252; d) C. Madic, M. Lecomte, P. Baron, B. Baullis, *C. R. Phys.* **2002**, *3*, 797–811; e) H. H. Dam, D. N. Reinhoudt, W.

Verboom, *Chem. Soc. Rev.* **2007**, *36*, 367–377, and references cited therein; f) S. A. Ansari, P. Pathak, P. K. Mohapatra, V. K. Mauchand, *Chem. Rev.* **2012**, *112*, 1751–1772; g) S. A. Ansari, P. Pathak, P. K. Mohapatra, V. K. Mauchand, *Sep. Purif. Rev.* **2011**, *40*, 43–76; h) A. B. Patil, P. Pathak, V. S. Shinde, S. V. Godbole, P. K. Mohapatra, *Dalton Trans.* **2013**, *42*, 1519–1529; i) F. W. Lewis, M. J. Hudson, L. M. Harwood, *Synlett* **2011**, 2609–2632, and references cited therein; j) P. J. Panak, A. Geist, *Chem. Rev.* **2013**, *113*, 1199–1236; k) M. J. Hudson, L. M. Harwood, D. M. Laventine, F. W. Lewis, *Inorg. Chem.* **2013**, *52*, 3414–3428.

[2] a) C. Liao, S. Wu, F. Cheng, S. Wang, Y. Liu, B. Zhang, C. Yan, *J. Rare Earths* **2013**, *31*, 331–336; b) GAO010–617R, *Rare Earth Materials in the Defense Supply Chain*, U. S. Government Accountability Office, **2010**, Washington, DC; c) G. A. Green, *The Defense Implications of Rare Earth Shortages* NCPA Rept. Brief 112, Sept. **2012**.

[3] a) B. M. Rapko, E. N. Duesler, P. H. Smith, R. T. Paine, R. R. Ryan, *Inorg. Chem.* **1993**, *32*, 2164–2174; b) U. Engelhardt, B. M. Rapko, E. N. Duesler, D. Frutos, R. T. Paine, *Polyhedron* **1995**, *14*, 2361–2369; c) E. M. Bond, X. Gan, J. R. FitzPatrick, R. T. Paine, *J. Alloys Compd.* **1998**, *271–273*, 172–175; d) E. M. Bond, E. N. Duesler, R. T. Paine, M. P. Neu, J. H. Matonic, B. L. Scott, *Inorg. Chem.* **2000**, *39*, 4152–4155; e) E. M. Bond, E. N. Duesler, R. T. Paine, H. Nöth, *Polyhedron* **2000**, *19*, 2135–2140; f) X.-M. Gan, S. Parveen, W. L. Smith, E. N. Duesler, R. T. Paine, *Inorg. Chem.* **2000**, *39*, 4591–4598; g) J. H. Matonic, M. P. Neu, A. E. Enriquez, R. T. Paine, B. L. Scott, *J. Chem. Soc., Dalton Trans.* **2002**, 2328–2332; h) X.-M. Gan, E. M. Duesler, R. T. Paine, *Inorg. Chem.* **2001**, *40*, 4420–4427; i) J. H. Matonic, A. E. Enriquez, B. L. Scott, R. T. Paine, M. P. Neu, *Nucl. Sci. Technol.* **2002**, *3*, 100–105; j) R. T. Paine, E. M. Bond, S. Parveen, N. Donhart, E. N. Duesler, K. A. Smith, H. Nöth, *Inorg. Chem.* **2002**, *41*, 444–448; k) X.-M. Gan, R. T. Paine, E. N. Duesler, H. Nöth, *Dalton Trans.* **2003**, 153–159; l) X.-M. Gan, B. M. Rapko, E. N. Duesler, I. Binyamin, R. T. Paine, B. P. Hay, *Polyhedron* **2005**, *24*, 469–474; m) S. Pailloux, C. E. Shirima, A. D. Ray, E. N. Duesler, R. T. Paine, J. R. Klaehn, M. E. McIlwain, B. P. Hay, *Inorg. Chem.* **2009**, *48*, 3104–3113; n) S. Pailloux, C. E. Shirima, A. D. Ray, E. N. Duesler, K. A. Smith, R. T. Paine, J. R. Klaehn, M. E. McIlwain, B. P. Hay, *Dalton Trans.* **2009**, 7486–7493.

[4] a) I. Binyamin, S. Pailloux, E. N. Duesler, B. M. Rapko, R. T. Paine, *Inorg. Chem.* **2006**, *45*, 5886–5892; b) I. Binyamin, S. Pailloux, B. P. Hay, E. N. Duesler, B. M. Rapko, R. T. Paine, *J. Heterocycl. Chem.* **2007**, *44*, 99–103; c) S. Pailloux, I. Binyamin, S. Kim, L. M. Deck, B. M. Rapko, B. P. Hay, E. N. Duesler, R. T. Paine, *J. Org. Chem.* **2007**, *72*, 9195–9202; d) S. Pailloux, I. Binyamin, L. M. Deck, B. P. Hay, L. N. Zakharov, W. S. Kassel, A. L. Rheingold, R. T. Paine, *Polyhedron* **2009**, *28*, 3979–3984.

[5] a) E. M. Bond, U. Engelhardt, T. P. Deere, B. M. Rapko, R. T. Paine, *Solvent Extr. Ion Exch.* **1997**, *15*, 381–400; b) E. M. Bond, U. Engelhardt, T. P. Deere, B. M. Rapko, R. T. Paine, *Solvent Extr. Ion Exch.* **1998**, *16*, 967–983; c) K. L. Nash, C. Lavallette, M. Borkowski, R. T. Paine, X.-M. Gan, *Inorg. Chem.* **2002**, *41*, 5849–5858; d) J. Sulakova, R. T. Paine, M. Chakravarty, K. L. Nash, *Sep. Sci. Technol.* **2012**, *47*, 2015–2023.

[6] Z. Guo, G.-H. Kim, I. Shin, J. Yoon, *Biomaterials* **2012**, *33*, 7818–7827.

[7] All H-atoms and lattice solvents are omitted from ORTEP views except as specifically noted in the text. Selected bond lengths are provided in the Supporting Information.

[8] P. Sengupta, A. E. Henkes, M. K. Kumar, H. Zhang, D. Y. Son, *Synthesis* **2008**, 79–86.

[9] R. N. Salvatore, A. S. Nagle, K. W. Jung, *J. Org. Chem.* **2002**, *67*, 674–683.

[10] C. B. Singh, V. Kavala, A. K. Samal, B. K. Patel, *Eur. J. Org. Chem.* **2007**, 1369–1377.

[11] J. L. Moore, S. M. Taylor, V. A. Soloshonok, *ARKIVOC* **2005**, *6*, 287–292.

[12] T. Yajima, M. Okajima, A. Odami, O. Yamauchi, *Inorg. Chim. Acta* **2002**, *339*, 445–454.

[13] a) G. R. Newkome, V. K. Gupta, F. R. Fronczek, S. Pappalardo, *Inorg. Chem.* **1984**, *23*, 2400–2408; b) T. Darbe, C. Dubs, E. Rusanov, H. Stoeckli-Evans, *Eur. J. Inorg. Chem.* **2002**, 3284–3291.

[14] A. Fürstner, M. Alcarazo, H. Krause, C. W. Lehmann, *J. Am. Chem. Soc.* **2007**, *129*, 12676–12677.

[15] a) C. Li, L. S. Rittman, A. S. Tsiftsoglou, K. K. Bhargava, A. C. Sartorelli, *J. Med. Chem.* **1978**, *21*, 874–877; b) U. P. Chaudhuri, L. R. Whiteaker, L. Yang, R. P. Houser, *Dalton Trans.* **2006**, 1902–1908.

[16] a) P. G. Jessop, L. Phan, A. Carrier, S. Robinson, C. J. Durr, J. R. Harjani, *Green Chem.* **2010**, *12*, 809–814, and references cited therein; b) P. G. Jessop, *Green Chem.* **2011**, *13*, 1391–1398.

[17] a) S. B. Shen, H. Ishida, *J. Appl. Polym. Sci.* **1996**, *61*, 1595–1605; b) T. Uyar, J. Hacaloglu, H. Ishida, *J. Appl. Polym. Sci.* **2013**, *127*, 3114–3123, and references cited therein.

[18] a) S. Chirachanchai, A. Laobuthee, S. Phontamrag, W. Siripattanasarakit, H. Ishida, *J. Appl. Polym. Sci.* **2000**, *77*, 2561–2568; b) A. Laobuthee, S. Chirachanchai, H. Ishida, K. Tashiro, *J. Am. Chem. Soc.* **2001**, *123*, 9947–9955; c) A. Laobuthee, H. Ishida, S. Chirachanchai, *J. Inclusion Phenom. Macrocyclic Chem.* **2003**, *47*, 179–185; d) S. Chirachanchai, S. Phongtamrug, A. Laobuthee, *Chem. Lett.* **2003**, *32*, 432–433; e) T. Rungsimanon, A. Laobuthee, M. Miyata, S. Chirachanchai, *J. Inclusion Phenom. Macrocyclic Chem.* **2008**, *62*, 333–338; f) S. Chirachanchai, A. Laobuthee, S. Phongtamrug, *J. Heterocycl. Chem.* **2009**, *46*, 714–721; g) S. Chirachanchai, T. Rungsimanon, S. Phongtamrug, M. Miyata, A. Laobuthee, *Tetrahedron* **2009**, *65*, 5855–5861; h) A. Kaewvilai, T. Rungsimanon, N. Koonsaeng, S. Chirachanchai, A. Laobuthee, *Asian J. Chem.* **2010**, *22*, 7628–7640.

[19] B. P. Hay, R. D. Hancock, *Coord. Chem. Rev.* **2001**, *212*, 61–78.

[20] a) B. P. Hay, J. R. Rustad, C. J. Hostetler, *J. Am. Chem. Soc.* **1993**, *115*, 11158–11164; b) B. P. Hay, D. Zhang, J. R. Rustad, *Inorg. Chem.* **1996**, *35*, 2650–2658; c) M. L. Dietz, A. H. Bond, B. P. Hay, R. Chiarizia, V. J. Huber, A. W. Herlinger, *Chem. Commun.* **1999**, 1177–1178; d) B. P. Hay, D. A. Dixon, R. Vargas, J. Garza, K. N. Raymond, *Inorg. Chem.* **2001**, *40*, 3922–3935; e) G. J. Lumetta, B. M. Rapko, P. A. Garza, B. P. Hay, R. D. Gilbertson, T. J. R. Weakley, J. E. Hutchison, *J. Am. Chem. Soc.* **2002**, *124*, 5644–5645; f) B. P. Hay, T. K. Firman, *Inorg. Chem.* **2002**, *41*, 5502–5512; g) B. P. Hay, A. A. Oliferenko, J. Uddin, C. Zhang, T. K. Firman, *J. Am. Chem. Soc.* **2005**, *127*, 17043–17053; h) B. W. Parks, R. D. Gilbertson, J. E. Hutchison, E. Rather Healy, T. J. R. Weakley, B. M. Rapko, B. P. Hay, S. I. Sinkov, G. A. Broker, R. D. Rogers, *Inorg. Chem.* **2006**, *45*, 1498–1507.

[21] a) D. Rosario-Amorin, S. Ouizem, D. A. Dickie, Y. Wen, R. T. Paine, J. Gao, J. K. Grey, A. de Bettencourt-Dias, B. P. Hay, L. H. Delmau, *Inorg. Chem.* **2013**, *52*, 3063–3083; b) S. L. Pailloux, D. Rosario-Amorin, M. Chakravarty, J.-M. Camus, K. A. Smith, E. N. Duesler, D. A. Dickie, R. T. Paine, K. K. Klausmeyer, D. A. Padron, B. P. Hay, L. H. Delmau, *Z. Anorg. Allg. Chem.* **2013**, *639*, 1101–1116.

[22] K. Nagasawa, in: *Superbases for Organic Synthesis* (Ed.: T. Ishikawa), John Wiley & Sons, Chichester, UK, **2009**.

[23] F. T. Edelmann, *Adv. Organomet. Chem.* **2008**, *57*, 183–353.

[24] a) T. Ishikawa, *Chem. Pharm. Bull.* **2010**, *58*, 1555–1564; b) K. Suda, N. Saito, T. Kumamoto, W. Nakanishi, M. Kawahata, K. Yamaguchi, Y. Ogura, K. T. Suzuki, T. Ishikawa, *Heterocycles* **2009**, *77*, 375–387.

[25] a) A. Hoffmann, J. Börner, U. Flörke, S. Herres-Pawlis, *Inorg. Chim. Acta* **2009**, *362*, 1185–1193; b) J. Börner, I. Dos Santos Vieira, M. D. Jones, A. Döring, D. Kuckling, U. Flörke,

S. Herres-Pawlis, *Eur. J. Inorg. Chem.* **2011**, 4441–4456, and references cited therein.
[26] P. Roquette, C. König, O. Hübner, A. Wagner, E. Kaifer, M. Enders, H.-J. Himmel, *Eur. J. Inorg. Chem.* **2010**, 4770–4782.
[27] M. L. Cole, P. C. Junk, *Dalton Trans.* **2003**, 2109–2111.
[28] a) *APEX 2*, Bruker AXS, Inc., Madison, WI, **2007**; b) *SAINT+*, v.7.01, **2003** Bruker AXS, Inc., Madison, WI 53719; c) *SADABS*, v.2.10, **2003**, G. M. Sheldrick, University of Göttingen, Germany.
[29] *SHELXL-97*, Bruker AXS, Inc., Madison, WI 53719, **2008**.
[30] a) P. van der Sluis, A. L. Spek, *Acta Crystallogr., Sect. A* **1990**, *46*, 194–201; b) A. L. Spek, *Acta Crystallogr., Sect. A* **1990**, *46*, C34.
[31] a) N. L. Allinger, Y.-H. Yuh, J.-H. Lii, *J. Am. Chem. Soc.* **1989**, *111*, 8551–8566; b) J.-H. Lii, N. L. Allinger, *J. Am. Chem. Soc.* **1989**, *111*, 8566–8575; c) J.-H. Lii, N. L. Allinger, *J. Am. Chem. Soc.* **1989**, *111*, 8576–8582.
[32] B. P. Hay, *Coord. Chem. Rev.* **1993**, *126*, 177–236.
[33] *PCModel*, v.9.3, Serena Software, Bloomington, Indiana, USA.

Received: January 23, 2014
Published Online: April 8, 2014

