Nontrigonal constraint enhances 1,2-addition reactivity of phosphazenes†

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The syntheses and 1,2-addition reactivities of nontrigonal phosphazenes supported by triionic tricoordinating chelates of the type \( \text{L}_3\text{P} = \text{Ndipp} \) (3: \( \text{L}_3 = \text{N}[-\text{CH}(-\text{Bu})\text{O}]_2 \); 4: \( \text{L}_3 = \text{N}[-\text{MeC}_6\text{H}_4\text{O}]_2 \); dipp = 2,6-disopropylphenyl) are reported. These compounds are characterized by multinuclear NMR and single-crystal X-ray diffraction experiments. Distorted phosphazenes 3 and 4 are shown to add \( \text{B} = \text{H}, \text{B} = \text{O} \), and \( \text{Si} = \text{H} \) bonds across the formal \( \text{P} = \text{N} \) double bond, and their reactivities are contrasted with acyclic analogues. Derivatives of phosphazene 3 bearing sterically unencumbered \( \text{N} \)-substituents readily dimerize to form the corresponding cyclodiphosphazanes; compounds with sterically demanding \( \text{N} \)-substituents are interconvertible between their monomeric and dimeric forms. The enhanced electrophilicity of the phosphorus center in nontrigonal phosphazenes 3 and 4 is rationalized by DFT calculations. Gas phase fluoride ion affinities are computed to be markedly higher for distorted phosphazenes, while proton affinities are largely unaffected by geometric distortion. These results are interpreted to suggest that distortion from pseudotetrahedral geometry results in stabilization of the P-based LUMO, while HOMO energies are essentially unchanged.

Apart from this nitrogen-based reactivity, phosphazenes also have been employed in a number of transformations that leverage the vicinal ambiphilic character of the \( \text{P} = \text{N} \) unit. Chief among this class of reactions are metathetical transformations stemming from formal \( (2 + 2) \) addition/elimination of unsaturated organic compounds at the phosphazene \( \text{P} = \text{N} \) moiety, of which the aza-Wittig and related imine metathesis reaction are representative. An increasingly important use of phosphazenes comes in the Staudinger ligation reaction, which has become an important tool in bioconjugation chemistry.

Recently, we have been investigating the connection between equilibrium ground-state structure and reactivity in a class of nontrigonal phosphabicyclic compounds. We have documented that the distorted molecular geometries for these tricoordinate phosphorus compounds have a significant impact on both their electronic structure and reactivity. For instance, we have reported that Arduengo’s T-shaped phosphorus compound 1 (Fig. 1 top) supports transfer hydrogenation catalysis and \( \text{N} = \text{H} \) oxidative addition reactivity. In addition, we reported the synthesis of \( \text{C}_{12} \)-symmetric phosphorus compound 2 (Fig. 1, top) and its ability to undergo \( \text{E} = \text{H} \) bond activation reactivity \( (\text{E} = -\text{OR}, -\text{NHR}, -\text{BR}_2) \) at phosphorus through a ligand-cooperative mechanism.

Based on this precedent, we wished to ascertain the extent to which the distinctive reactivity traits of nontrigonal phosphorus compounds 1 and 2 might range beyond the tricoordinate state to support interesting chemical properties of their distorted \( \sigma^4,\lambda^5 \)-phosphazene derivatives. In this study, we report a combined theoretical and experimental treatment of

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1. Introduction

Phosphazenes, \( \sigma^4,\lambda^5 \)-phosphorus compounds of the form \( \text{R}_3\text{P} = \text{NR} \), comprise a broad class of functionally diverse main group inorganic molecules. The properties and reactivities of phosphazenes can be modulated over a wide range depending on substitution at the two heteroatom positions. In many circumstances, the \( \text{P} = \text{N} \) unit proves quite inert; indeed, the robustness of the \( \text{P} = \text{N} \) moiety forms the basis for the many remarkable applications of polyphosphazene inorganic/organic hybrid materials.

As might be expected on the basis of the differing electronegativities of phosphorus and nitrogen, however, the polarization of the formal \( \text{P} = \text{N} \) double bond \( (\text{i.e.}, \text{contributing Lewis structures} \text{R}_3\text{P} = \text{NR} \leftrightarrow \text{R}_3\text{P}^- \text{N} \text{R}^-) \) also gives rise to numerous applications for phosphazenes as nitrogen-based electron pair donors. For instance, phosphazenes are known to be strong donor ligands for transition metals. Phosphazenes have found synthetic use as strong, non-ionic organic superbases; the tetrameric triaminophosphazene superbase \( \text{t-Bu-P}_4 \) displays exceptionally high Brønsted-Lowry basicity and has been investigated for a variety of base-mediated transformations.

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phosphazenes based on supporting structures 1 and 2 which validate the hypothesis that imposition of a geometric constraint at positions ancillary to the P=N unit enhances vicinal ditopic ambiphilicity of these phosphazenes. We also show that 1,2-reactivity of the P=N unit leads to facile addition of σ-bonded B–H, B–O, and Si–H reagents across the P=N moiety. In total, the results establish a rational framework for the design of bespoke phosphazenes with novel properties and reactivities that expand the functional role of this important class of main group compounds.

2. Results and discussion

2.1. Computational model of the phosphazene distortion coordinate

A computational appraisal of the consequence of molecular distortion on phosphazene frontier electronic structure illustrates the theoretical framework underlying our experimental study. With the parent phosphazene H3P=NH (Fig. 2, inset) as a minimalistic model system, orbital and overall electronic energies were computed as a function of internal bond angle \( \angle H_1-P-H_3 (\alpha) \) in the range \( 90^\circ < \alpha < 180^\circ \) at the M06-2X/def2-TZVP level of theory as implemented in the ORCA 4.0.0 software package. For each structure scanned, the dihedral angle \( \angle H_1-P-N-H_4 \) was relaxed to minimize energy associated with rotation about the P=N formal double bond; bond lengths were held constant at values obtained from the equilibrium geometry of H3P=NH (\( d_{P-H} = 1.44 \) Å, \( d_{P-N} = 1.61 \) Å, \( d_{N-H} = 1.02 \) Å); these parameters are in good agreement with those found in previous computational studies of H1,P=NH.3,17

Fig. 2. Relative electronic energy (dashed, square) and HOMO/LUMO energies (solid, circle) in H3P=NH as a function of bond angle, calculated at the M06-2X/def2-TZVP level of theory. HOMO and LUMO Kohn–Sham orbitals are shown for \( \alpha = 100^\circ \) and \( 180^\circ \).

Deviations from the equilibrium geometry \( (\alpha = 97.9^\circ) \) predictably lead to increases in overall energy (Fig. 2, dotted line). Notwithstanding this fact, the energy of the highest occupied orbital \( (\epsilon_{LUMO}) \) remains more or less constant across the scanned coordinate. Visual inspection of the relevant orbitals provides for a qualitative interpretation of this observation; highest occupied molecular orbitals are found to be mostly nitrogen-based, corresponding largely to the N lone pair \( (n_N) \) with minor contributions from the ancillary phosphorus substituents.

By contrast, the energy of the lowest unoccupied orbital \( (\epsilon_{HOMO}) \) decreases as the bond angle \( \alpha \) increases, ultimately resulting in stabilization of more than 3 eV as LUMO takes on increasing s-orbital character in the distortion to seesaw geometry \( (\alpha = 180^\circ) \). This electronic picture suggests that the nontrigonal distortion of phosphazenes should retain the Lewis basicity of the N position but dramatically increase the Lewis acidity of the P position. We posit that the juxtaposition of donor and acceptor character at adjacent atoms should lead to an increase in 1,2-ambiphilic reactivity of the P=N unit, in analogy to well-established chemistry of early transition metal imido (M=NR) complexes.18 We sought to confirm these theoretical predictions experimentally with a suite of phosphazene compounds.

2.2. Phosphazene synthesis and characterization

2.2.1 Synthesis and spectroscopy. The requisite phosphazenes are easily prepared by Staudinger imination of tricoordinate phosphorus platforms. Reaction of C25\textsuperscript{2-}symmetric phosphorus compound 1 with 2,6-diisopropylphenyl azide (C6D6, 40 °C, 16 h), followed by removal of volatiles and trituration of the residue in pentane, produced a white solid whose \(^{31}\text{P}([\text{H}])\) NMR spectrum displayed a resonance at \( \delta 7.3 \) ppm; the observed chemical shift is consistent with compositionally similar O,N,O-substituted phosphazenes previously reported in the literature.40 In the \(^1\text{H}\) NMR spectrum, both vinylic protons (\( \delta 5.49 \) ppm) and \( \text{^1}H \) groups (\( \delta 0.91 \) ppm) on the O,N,O-support scaffold of 3 give rise to a single resonance, respectively, suggesting a time-averaged molecular geometry of C2 molecular symmetry or higher. In contrast to the planar starting material 1, the \( J_{\text{F-P}} \) scalar coupling constant between phosphorus and the vinylic hydrogen nuclei for 3 (\( J_{\text{F-P}} = 29 \) Hz) is discernible and modest in magnitude. Arduengo previously noted an empirical relationship between the magnitude of this \( J_{\text{F-P}} \) value and the extent of molecular folding of the O,N,O-
supporting ligand in related σ^4-P compounds. On this basis, we infer that the bicyclic O,N,O ligand backbone is distorted from planarity by folding along the P–N axis. We therefore assigned the structure of 3 as in Scheme 1.

Similarly, compound 4 was prepared by the reaction of 2 with 1 equiv. of 2,6-diisopropylphenyl azide (C_{6}D_{6}, RT, 12 h) and subsequent recrystallization from a solution of pentane and dichloromethane. The $^{31}$P{H} NMR spectrum of this compound showed a resonance at δ 14.5 ppm, consistent with typical values for tetraazaphosphazenes. The spectroscopic equivalence of both ligand N-methyl substituents in the $^1$H NMR spectrum suggest time-averaged $C_s$ or higher symmetry, as with compound 3.

For the purpose of comparison, acyclic phosphazene analogues 7 and 8 were likewise synthesized from the corresponding phosphorus compounds 5 and 6 (Scheme 2).

2.2.2 Solid state structures. Crystalline solids of 3 and 4 suitable for X-ray diffraction were grown by vapor diffusion from a dichloromethane/pentane system, and their solid state structures were determined (Fig. 3, Table 1). As expected, both structures exhibit nontrigonal distortion enforced by the ligand. Acyclic O,N,O- (7) and N,N,N- (8) phosphazene analogues also were analyzed by X-ray diffraction of single crystalline samples obtained from dichloromethane/pentane solution.

The solid state structure of 3 displays substantial opening of the O_{1}–P_{1}–O_{2} bond angle relative to the acyclic phosphazene 7; the bond angle in 3 (112.62(6)°) is 16° wider than that of 7 (96.70(8)°). The increase in O_{1}–P_{1}–O_{2} bond angle in 3 is complemented by a moderate (<5–10°) decrease in internal bond angles O_{1}–P_{1}–O_{2}. Additionally, the N_{4}–P_{1}–N_{2} angle likewise increases in 3 (124.96(7)°) relative to 7 (116.46(11)°) in order to restrict unfavorable steric interactions between the N-dipp substituent and the ligand backbone. Thus, the solid state structure of phosphazene 3 corresponds to a deviation from idealized pseudo-tetrahedral geometry along the distortion coordinate illustrated in Fig. 2.

Similarly, N,N,N-phosphabicyclic phosphazene 4 has an expanded N_{7}–P_{1}–N_{4} bond angle of 4 (119.73(6)°), 14° greater than the average angle in 8 (105.15(15)°). Furthermore, the N_{7}–P_{1}–N_{3} and N_{7}–P_{1}–N_{4} endocyclic angles were generally smaller relative to 8. As with constrained phosphazene 3, there was also an expansion of the N_{7}–P_{1}–N_{4} bond angle in 4 (129.22(6)°) versus 8 (109.99(15)°, average of 3 angles), constituting a difference of 19°; this difference is greater than that of the 3/7 pair and is likely a result of increased steric congestion imposed by the N-methylanilides of 4.

These solid state structures confirm our hypothesis that imposing geometric constraints via a bicyclic ligand framework results in a nontrigonal geometry along the distortion coordinate toward see-saw molecular structures.

Fig. 3 Thermal ellipsoid plots of phosphazenes 3, 7, 4, and 8 rendered at 50% probability level. Hydrogen atoms omitted for clarity.
Table 1: Selected bond distances (Å) and angles (°) for phosphazenes 3, 4, 7, and 8.

<table>
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<th>Metric</th>
<th>3</th>
<th>4</th>
<th>7</th>
<th>8</th>
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<tr>
<td>d(P1–N1)</td>
<td>1.5069(14)</td>
<td>1.4810(17)</td>
<td>1.5309(11)</td>
<td>1.525(3)</td>
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<tr>
<td>d(P1–N2)</td>
<td>1.6903(13)</td>
<td>1.613(2)</td>
<td>1.7095(10)</td>
<td>1.644(3)</td>
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<tr>
<td>d(P1–O1)</td>
<td>1.6044(12)</td>
<td>1.6044(15)</td>
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<tr>
<td>d(P1–O2)</td>
<td>1.5962(11)</td>
<td>1.5985(15)</td>
<td></td>
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<tr>
<td>d(P1–N3)</td>
<td>1.6723(12)</td>
<td>1.639(3)</td>
<td></td>
<td></td>
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<tr>
<td>d(P1–N4)</td>
<td>1.6591(11)</td>
<td>1.632(3)</td>
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Values in kcal mol⁻¹.

Table 2: Gas phase fluoride ion affinities and proton affinities of phosphazenes 3, 4, 7, and 8 calculated at the M06-2X/def2-TZVP level of theory.

<table>
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<tr>
<th>Compound</th>
<th>FIAa</th>
<th>PAa</th>
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<td>3</td>
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</tr>
<tr>
<td>7</td>
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<tr>
<td>4</td>
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<td>246</td>
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<td>8</td>
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</table>

2.2.3 Computational comparison of constrained and unconstrained compounds. We performed gas phase fluoride ion affinity (FIA) and proton affinity (PA) calculations on 3, 4, 7, and 8 at the M06-2X/def2-TZVP level of theory as a way of quantifying their respective Lewis acidities and basicities (see ESI† for full details). FIA values were calculated via Christe’s method, summarized in eqn (1), and PAs were similarly computed according to eqn (2). The collected values are reported in Table 2.

\[ \text{CF}_2O + [R_3P(F)\equiv NR'] \rightarrow \text{CF}_2O^- + R_3P^- + NR' \Delta H_{\text{rxn}} = \text{FIA} \]  

(1)

\[ [R_3P\equiv N(H)R']^+ \rightarrow H^+ + R_3P^- + NR' \Delta H_{\text{rxn}} = \text{PA} \]  

(2)

Fluoride ion affinities for constrained phosphazenes 3 and 4 are significantly greater (>20 kcal mol⁻¹ difference in each case) than their unconstrained analogues 7 and 8. This result conforms with qualitative predictions from the model system H₃P=N-NH (vide supra, Section 2.1.1); upon distortion from pseudo-tetrahedral geometry, the phosphorus-based LUMOs decrease in energy, allowing for stronger interactions of exogenous anions like F⁻ with nontrigonal 3 and 4 than with trigonal compounds 7 and 8.

Differences in proton affinities, on the other hand, are much smaller in magnitude. For instance, the computed PAs for compounds 3 and 7 are 238 kcal mol⁻¹ and 239 kcal mol⁻¹, respectively. For compounds 4 and 8, the PAs are 246 kcal mol⁻¹ and 258 kcal mol⁻¹, respectively. Given the magnitude of the calculated proton affinities, the difference in calculated PAs for 3/7 and 4/8 does not exceed 6% overall. This outcome is in accord with the interpretation from calculations in Section 2.1.1 in which molecular distortion would not be expected to affect significantly the N-based HOMOs responsible for Lewis basicity.

2.3. Monomer–dimer speciation of nontrigonal phosphazenes

2.3.1 Effect of trinationic chelate on monomer–dimer equilibrium of phosphazenes. Although the monomeric phosphazene 3 could be prepared and characterized as indicated above, prolonged standing of solutions (ca. 3 d) at 60 °C led to the emergence of a new species with a low-field ³¹P NMR resonance (δ = −26.9 ppm). The formation and intensity of this new signal followed a concentration dependence in [3], suggesting a possible bimolecular origin. In accord with this observation, the identity of the new species was ultimately confirmed by single crystal X-ray diffraction analysis to be that of a head-to-tail homodimeric 1,3-diaza-2,4-diphosphetidine (cyclophanazine) 3′, which could be selectively crystallized from benzene solutions of 3/3′ (Scheme 3).

Cyclophanazine 3′ is found to crystallize in the centrosymmetric monoclinic space group C2/c, with one phosphazene monomer fragment in the asymmetric unit and the dimer generated by symmetry. The structural data indicate local trigonal bi pyramidal geometry about each phosphorus center, where the formerly imino nitrogen atoms occupy one equatorial and one apical site (Fig. 4). The most distinctive feature of this stereochemical arrangement is the dissymmetric P–N bond distances within a planar diamond-like P₀N₂ core. As might be expected on the basis of the Rundle–Pimentel model of bonding in pentacoordinate p-block compounds, the axial P–N bond is significantly longer (dP–N = 1.783(3) Å) than the equatorial P–N bonds (dP–N = 1.665(3) Å). Both bond distances are elongated as compared to monomeric 3 (dP–N = 1.5069(14) Å). In short, the structural metrics are consistent with a superposition of the Lewis structures for 3′, displayed in Scheme 3.
Dissolution of a single-crystalline sample of 3’ in C6D6 at ambient temperature resulted in repopulation of the mixture containing both dimer 3’ and monomer 3 as judged by 1H and 31P NMR spectroscopy. Consequently, we conclude that the formal 2 + 2 dimerization of 3 to 3’ is reversible, as illustrated in Scheme 3. Notwithstanding the apparent dynamic nature of the monomer–dimer equilibrium, the appearance of two distinct resonances for 3 and 3’ in the 31P NMR spectra is most consistent with a slow interconversion relative to the NMR timescale.

In contrast to the deformed O,N,O-phosphazene 3, dimerization of the constrained N,N,N-phosphazene 4 was not observed under any conditions.5 We posit that in this case the steric crowding by N-Me substituents of the bicyclic ligand framework and imino N-substituent prohibits close approach of a second phosphazene as would be necessary for dimer formation. Additionally, the phosphorus center of 4 is less Lewis acidic than that of 3 (as revealed by FIA analysis above), so it is possible that decreased electrophilicity at P precludes sufficient driving force for phosphazene dimerization.

2.3.2 Effect of imino N-substituent on monomer–dimer equilibrium of O,N,O substituted phosphazenes. The identity of the imino N-substituent has a controlling effect on the rate and position of monomer–dimer equilibrium for phosphazenes based on O,N,O-platform 1. Whereas the N-dipp substituted phosphazene could be isolated in either monomeric (3) or dimeric (3’) forms, O,N,O-phosphazenes bearing less sterically encumbered N-substituents could be isolated only in their dimeric cyclodiphosphazane forms (Scheme 4). In a typical preparation, treatment of 1 with 1 equiv. of organoazide in C6D6 at 60 °C for 16 h gave only dimeric cyclodiphosphazanes with 31P NMR chemical shifts characteristic of five-coordinate phosphorus (Table 3). In situ 31P NMR experiments show that monomeric phosphazenes bearing N-tolyl [9, δ 9.9 ppm] moieties are detected as transient intermediates in the overall process, converting ultimately to the dimeric cyclodiphosphazane (9’, δ −44.6 ppm). By contrast, phosphazenes with electron-withdrawing (3,5-bis(trifluoromethyl)phenyl, 10’, δ −44.0 ppm) and alkyl (n-octyl, 11’, δ −39.6 ppm; cyclohexyl, 12’, δ −38.1 ppm) N-substituents were observed only in their dimeric cyclodiphosphazane forms.

The 31P NMR resonances of cyclodiphosphazanes 9’–12’ appear at noticeably lower field compared to 3’, suggesting a geometric distinction between the very bulky 2,6-diisopropylsubstituted cyclodiphosphazane and less sterically demanding congeners. Single crystals of dimeric N-tolyl derivative 9’ were obtained by slow evaporation of a benzene solution, and the structure was interrogated by X-ray diffraction (Fig. 5). Globally, compound 9’ adopts the same planar 1,3-diazao,2,4-diphosphetidine P2N2 diamond core structure as 3’. There are, however, notable metrical differences; the axial P–N (dP,N = 1.744(3) Å) and equatorial P–N (dP,N = 1.635(3) Å) bond lengths for N-tolyl cyclodiphosphazane 9’ are approximately 0.04 Å shorter than for N-dipp cyclodiphosphazane 3’. We infer that the reduced steric congestion about the P2N2 core for 9’ permits tighter association of the monomer subunits in a head-to-tail fashion that is manifest in the 31P isotropic chemical shielding differences. Congruent with this assessment, attempts to access monomeric phosphazenes 9–12 by heating of benzene solutions of 9’–12’ were unsuccessful; formal (2 + 2) dimerization appears to be prohibitively downhill in enthalpy and, therefore, irreversible for these less sterically congested cyclodiphosphazanes.

Formal [2 + 2]-cyclodimerization of phosphazene P=N units is well-precedented in the literature, specifically for phosphazenes bearing strongly electron-withdrawing P-substituents or

**Table 3** 31P NMR chemical shifts of phosphazene monomers and dimers

<table>
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<tr>
<th>Compound</th>
<th>δ (monomer)</th>
<th>δ (dimer)</th>
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<tr>
<td>3</td>
<td>7.3</td>
<td>−26.9</td>
</tr>
<tr>
<td>9</td>
<td>9.9</td>
<td>−44.6</td>
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<td>10</td>
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<tr>
<td>11</td>
<td>−2</td>
<td>−39.6</td>
</tr>
<tr>
<td>12</td>
<td>−2</td>
<td>−38.1</td>
</tr>
</tbody>
</table>

*Chemical shift referenced to 85% H3PO4 (δ = 0.0 ppm). Spectra recorded in C6D6 at 293 K. Monomer not observed.*
where relief of ring strain provides a driving force. That geometrically constrained O,N,O-phosphazenes (9’–12’) readily dimerize is thus a qualitative indication of the marked Lewis acidity of these phosphorus centers as compared to their acyclic congeners. Furthermore, the sum of the observations concerning the monomer–dimer specification of distorted phosphazenes 3/3’ evidences a propensity for 1,2-ambiphilic reactivity of the P=N unit, suggesting that intermolecular 1,2-additions of exogenous reagents might be feasible.

2.4 1,2 addition reactivity of nontrigonal phosphazenes

2.4.1 B–H addition reactions. To investigate reactivity of the P=N unit in deformed phosphazenes 3 and 4, we elected to attempt the 1,2-addition of σ-bonded E–H small molecules. To this end, treatment of O,N,O-phosphazene 3 with 1 equiv. of pinacolborane (HBpin) in C6D6 at room temperature resulted in rapid consumption of the starting materials and formation of a single new compound with a 31P NMR resonance at δ = 43.7 ppm presenting as a doublet of triplets (J = 837, 17 Hz). The magnitude of the larger coupling constant is indicative of a direct P–H linkage; existence of a P–H moiety was confirmed in 1H NMR spectra by the appearance of a doublet centered at δ 9.37 ppm with complementary coupling (JP–H = 837 Hz).

Although attempts to obtain a solid state structure of 13 from X-ray diffraction analysis were unsuccessful, these spectroscopic signatures are consistent with formation of hydrido amido phosphorane 13 in which the O,N,O-chelate spans two apical and one equatorial position about a phosphorus-centered trigonal bipyramid, and the hydride and borylame substituents reside in the equatorial plane. Further support for this assignment comes by way of analogy to previous results from our group. We reported previously that hydrido amido phosphoranes related to 13 are accessible via intermolecular N–H oxidative addition to 3.10 More specifically, the addition of 2,6-diisopropylamine to 3 gave a crystallographically characterized oxidative addition product (i.e. the des-boryl congener of 13) that exhibits spectroscopic features (31P δ = 51.4 ppm; JP–H = 841 Hz) in close agreement with those obtained for 13. In short, the combined data lend strong evidence to the structural assignment of the B–H addition product 13.

Likewise, treating N,N,N,N-phosphazene 4 with 1 equiv. of pinacolborane in C6D6 at ambient temperature quickly consumed starting materials and yielded a species 14 with a doublet 31P NMR signal at δ = 37.6 ppm (doublet, JP–H = 579 Hz). Complementary coupling was observed in the 1H NMR spectrum with a doublet resonance at δ 6.36 ppm. As with the reaction of 3 and HBpin, these spectral data are characteristic of pentacoordinated hydrido amido phosphorane featuring a direct P–H bond. By analogy to previous results on the intermolecular N–H oxidative addition of 2,6-diisopropylamine to 4,11 we posit the assignment of 14 as in Scheme 5 with a folded non-meridional N,N,N-ligand, equatorial N-dipp substituent, and an axial hydride.

By contrast to 3 and 4, acyclic O,N,O- and N,N,N-phosphazenes 7 and 8 were unreactive with respect to pinacolborane under identical reaction conditions. Additionally, none of the dimeric cyclodiphosphazanes 9’–12’ were found to undergo reaction with HBpin. We conclude, therefore, that the ability of the phosphazenes 3 and 4 to undergo 1,2-addition of H–Bpin is dependent on the distorted structure enforced by the trianionic heteroatom supporting structures, and that access to the monomeric form of the phosphazene is critical for intermolecular addition.

2.4.2 B–O addition reactions. The deformed O,N,O-phosphazene 3 was also able to add B–O σ bonds across the P=N unit. Addition of 1 equiv. of n-butoxy catecholborane to a C6D6 solution of 3 at room temperature (Scheme 6) resulted in consumption of 3 with concomitant generation of a new 31P NMR singlet resonance at δ = −31.4 ppm indicative of penta-coordinated phosphorus species 15; scalar coupling could not be resolved. The corresponding 1H NMR spectrum featured a resonance at δ 5.33 ppm (doublet, JP–H = 17 Hz), which can be attributed to coupling between the phosphorus center and the vinyl protons of the O,N,O-ligand. The magnitude of this
coupling is smaller than would be expected for $\sigma^5$-phosphorus compounds with a planar, meridional $O,N,O$-chelate. This result suggests that antiperiplanarity between P and H has been lost; that is, the dihedral angle between the phosphorus and vinyl hydrogen atoms has decreased from 180° in accordance with the Karplus equation for $\gamma$ scalar coupling,\(^{27}\) implying that the $O,N,O$-framework adopts a folded geometry.

A single crystal suitable for X-ray diffraction was grown from benzene solution, and the solid state structure corroborates the above conclusion regarding $O,N,O$-folding (Fig. 6). A distinguishing feature of compound 15 is the unexpectedly short distance between the ligand amido N atom and the N-diphenyl bound boron ($d_{B-N} = 1.637(3)$ Å), consistent with the presence of a dative interaction $N2 \rightarrow B1$ in 15; pyramidalization of the boron atom evident in the solid state structure further evidences this conclusion. By consequence of this interaction, compound 15 may be viewed as a trigonal bipyramidal phosphorus compound supported by a tetracoordinating boron atom. The bond distances $d_{P-N} = 1.986(5)$ Å for [HP(OCH$_2$CH$_2$)$_3$N][BF$_4$],\(^{36}\) $d_{P-N} = 1.967(8)$ Å for [HP(MeNCH$_2$CH$_2$)$_3$N][BF$_4$],\(^{36}\) and $d_{P-N} = 1.990(16)$ Å for [HP(PhCH$_2$CH$_2$)$_3$N][BF$_4$] are comparable with bond distances of $d_{P-N} = 1.986(5)$ Å for [HP(OCH$_2$CH$_2$)$_3$N][BF$_4$],\(^{36}\) $d_{P-N} = 1.967(8)$ Å for [HP(MeNCH$_2$CH$_2$)$_3$N][BF$_4$],\(^{36}\) and $d_{P-N} = 1.990(16)$ Å for [HP(PhCH$_2$CH$_2$)$_3$N][BF$_4$]. Additionally, the apical P–N$_2$ bond in 15 is substantially longer than the equatorial P–N$_1$ bond (1.6195(18) Å, comprising a difference of more than 0.3 Å. As a consequence, the trans apical P–N$_2$ bond is found to be quite short (1.5906(16) Å); in fact, the apical P–O bond is shorter than the equatorial P–O bonds (1.6242(16) Å and 1.6252(16) Å). This observation runs counter to typical trigonal bipyramidal geometries, where the 3-center, 4-electron apical bonds are usually longer than the 2-center, 2-electron equatorial bonds. These unusual structural features of the B–O adduct of phosphazene 3 likely arise from molecular constraints imposed by the $O,N,O$-ligand and by the Lewis acidic boron atom.

Unlike phosphazene 3, $N,N,N$-ligated phosphazene 4 did not react with $n$-butoxy catecholborane, perhaps again due to increased steric congestion about the P=O unit. Likewise, acyclic analogues 7 and 8 were unreactive to B–O bonds.

**2.4.3 Si–H addition reactions.** In addition to activating B–H and B–O bonds, phosphazene 3 was reactive toward the Si–H bond of phenylsilane. Treating phosphazene 3 with phenylsilane in $\text{C}_6\text{H}_6$ at 50 °C for 16 h (Scheme 7) produced compound 16, which in the $^{31}\text{P}$ NMR spectrum displayed a doublet of triplets centered at $\delta = 44.2$ ppm ($J = 802$ Hz, 31 Hz). Likewise, a doublet resonance with a large coupling constant centered at $\delta = 9.44$ ppm ($J_{\text{P–H}} = 802$ Hz) was observed in the $^1\text{H}$ NMR spectrum. Another complementary doublet signal, corresponding to ligand vinyl protons, appeared at $\delta = 5.34$ ppm ($J_{\text{P–H}} = 31$ Hz). Analogous to other $\sigma^5$-$\lambda^3$-phosphorus compounds synthesized here (vide supra), the coupling constant of 31 Hz is indicative of a planar $O,N,O$-chelate, as in Scheme 7. Thus, these NMR spectra indicate that the Si–H bond of phenylsilane added across the $P=O$ bond of 3 to give a hydrido phosphoran with a $N$-silyl substituent.

$N,N,N$-Phosphazene 4 also reacted with phenylsilane, but at a slower rate than 3. The conversion of 4 and phenylsilane to hydrido phosphoran 17 was completed after 48 h of heating at 80 °C in $\text{C}_6\text{H}_6$. The resulting $^{31}\text{P}$ NMR spectrum showed one signal centered at $\delta = -29.1$ ppm ($J = 353$ Hz); the magnitude of the scalar coupling constant is characteristic of a $P$–H bond, consistent with the structure of the $\sigma^5$-phosphorus Si–H addition product 17. By analogy to other $N,N,N$-ligated...
compounds synthesized earlier, we expect the trianionic chelate to adopt a folded structure, as in Scheme 7.

Acyclic phosphazenes 7 and 8 were found to be unreactive at Si–H addition. The fact that compounds of this type are robust to silane addition has been exploited by Fontaine, who has shown that phosphazenes similar to 8 can be used as Lewis base-catalysts for catalysed hydrosilylation of CO2.30

The 1,2-addition of hydrosilane across the P≡N unit of a phosphazene has often been invoked, albeit usually in tandem with subsequent elimination from P(v) without direct observation of the elementary step. Kawashima has studied the intramolecular addition of a Si–H bond to a functionalized phosphazene.31 Phosphine-catalyzed variants of the Staudinger reduction of azides are believed to rely on the addition of hydrosilane to phosphazene intermediates to close the catalytic cycle.32 Relatedly, Denton has demonstrated that a phosphine-catalyzed Staudinger amidation reaction relies on the in situ reduction of a phosphazene, presumably initiated by 1,2-addition of hydrosilane.33 In each of these chemistries the silane reduction step likely proceeds via 1,2-addition via a trigonal bipyramidal hydrido amido phosphorane intermediate, but despite the prevalence of the 1,2-addition proposal, there do not exist discrete, well-characterized analogues of this key step. Our current results represent a rare well-defined addition reaction giving rise to stable pentacoordinate adducts that substantiate the notion of 1,2-addition of hydrosilanes to phosphazenes.

3. Conclusions

Constrained phosphabicyclic phosphazenes supported by trianionic scaffolding ONO- and NNO,N-ligands exhibit increased cyclodimerization and 1,2-addition reactions of B–H, B–O, and Si–H σ bonds as compared to acyclic congeners. The results of the combined experimental and theoretical studies above support the conclusion that nontrigonal distortion of phosphazenes leads to an enhancement of the 1,2-ambiphilic reactivity of the P≡N unit. In view of the multivarious roles of phosphazenes, the ability to master electronic structure and reactivity as a function of a modifiable parameter contributes to the discovery of novel applications. In conjunction with established approaches to synthetic tuning through substituent effects, the current results establish a rational geometry-based framework for modulating the reactivity of this important class of main group compounds, which may be leveraged in the design of functionally novel entities.

4. Experimental section

Full experimental details are available in the online ESI.†

4.1. Synthesis of 3

A solution of 1 (100 mg, 0.42 mmol) with 2,6-diisopropylphenyl azide (85 mg, 0.42 mmol) in C6D6 (1 mL) was stirred at 40 °C for 16 h. All volatiles were removed in vacuo, and the resulting residue was triturated with pentane. The crude product was obtained after filtration, and pure 3 was isolated as a white solid by recrystallization from a 10:1 dichloromethane/pentane solution (131 mg, 75% yield). 1H NMR (CδD6, 400 MHz): δ 7.23–7.21 (m, 2H), 7.12–7.07 (m, 1H), 7.07 (d, J = 7.7 Hz), 5.49 (d, J = 28.8 Hz), 3.83 (hept, J1H, J = 6.9 Hz), 1.40 (d, J = 6.8 Hz), 0.91 (s, 18H) ppm. 13C NMR (CδD6, 126 MHz): δ 154.19, 141.29 (d, J = 10.1 Hz), 32.64 (d, J = 8.6 Hz), 29.35, 26.89, 23.75 ppm. 31P NMR (CδD6, 162 MHz): δ 7.21 (t, J = 28.8 Hz) ppm. MS (ESI) calc’d for C16H17N3O2P (M+) 416.2593, found 416.2596.

4.2. Synthesis of 4

A solution of 2 (100 mg, 0.39 mmol) with 2,6-diisopropylphenyl azide (80 mg, 0.39 mmol) in C6D6 (1 mL) was stirred under ambient temperature for 12 h. The solvent was removed in vacuo, and the resulting solid product was recrystallized from 1 : 1 dichloromethane/pentane solution (121 mg, 72% yield). 1H NMR (CδD6, 400 MHz): δ 7.26 (d, J = 7.7 Hz, 2H), 7.16 (d, J = 7.4 Hz, 2H), 7.09–7.02 (m, 1H), 6.98–6.85 (m, 3H), 6.77 (d, J = 7.6 Hz, 3H), 6.23 (d, J = 7.7 Hz, 2H), 3.65 (hept, J = 6.9 Hz, 2H), 2.73 (d, J = 9.2 Hz, 6H), 1.22 (d, J = 6.9 Hz, 12H) ppm. 13C NMR (CδD6, 125 MHz): δ 141.38, 141.00 (d, J = 11.7 Hz), 138.09 (d, J = 17.6 Hz), 134.58 (d, J = 13.0 Hz), 124.56, 123.26, 121.34, 120.14, 116.34 (d, J = 10.2 Hz), 108.66 (d, J = 10.0 Hz), 29.29 (d, J = 18.9 Hz), 23.75 ppm. 31P NMR (CδD6, 162 MHz): δ 14.54 ppm. MS (ESI) calc’d for C30H49BN2O4P (M+) 430.2286, found 430.2290.

4.3. Representative B–H addition

A solution of 3 (30 mg, 0.07 mmol) and HBpin (9 mg, 0.07 mmol) in C6D6 (0.3 mL) was stirred at ambient temperature for 15 min. The solvent was removed in vacuo to afford the crude product (37 mg, 95% crude yield). 1H NMR (CδD6, 500 MHz): δ 9.38 (d, 1H, J = 837.7 Hz), 7.27–7.25 (m, 1H), 7.08–7.04 (m, 2H), 5.49 (d, 2H, J = 33.2 Hz), 3.62–3.56 (m, 2H), 1.53 (d, 6H, J = 6.6 Hz, 1.45) (d, 6H, J = 6.6 Hz, 6H), 1.19 (s, 12H), 1.15 (s, 18H) ppm. 13C NMR (CδD6, 126 MHz): δ 150.73 (d, J = 6.4 Hz, 147.14, 126.64, 124.52 (d, J = 4.4 Hz), 124.02, 123.42, 100.51 (d, J = 18.8 Hz), 82.52, 31.69, 28.25, 27.51, 24.66, 23.62, 23.26 ppm. 31P NMR (CδD6, 203 MHz): δ −43.02 (dt, J = 837.0, 31.5 Hz) ppm. MS (ESI) calc’d for C30H45BN2O4P (M–H+) 543.3518, found 543.3523.

4.4. Representative Si–H addition

A solution of 4 (50 mg, 0.12 mmol) and phenylsilane (13 mg, 0.12 mmol) in C6D6 (0.3 mL) was stirred at 80 °C for 48 h. All volatiles were removed in vacuo to afford 20 as a yellow oil (62 mg, 99% crude yield). 1H NMR (CδD6, 500 MHz): δ 7.32 (d, J = 7.1 Hz, 2H), 7.14–6.99 (m, 7H), 6.95 (t, J = 7.2 Hz, 3H), 6.87 (t, J = 7.7 Hz, 2H), 6.73 (t, J = 7.8 Hz, 2H), 6.37 (d, J = 7.5 Hz, 2H), 5.75 (d, J = 534.0 Hz, 1H), 5.05 (d, J = 5.8 Hz, 2H), 3.45–3.33 (m, 2H), 2.49 (d, J = 15.9 Hz, 6H), 1.15 (d, J = 6.8 Hz, 6H), 1.06 (d, J = 6.7 Hz, 6H) ppm. 13C NMR (CδD6, 126 MHz): δ 148.30 (d, J = 5.8 Hz), 137.93, 135.77 (d, J = 10.4 Hz), 134.65 (d, J = 14.5 Hz), 134.25, 133.46, 129.01, 127.16 (d, J = 3.6 Hz), 123.90 (d, J = 4.0 Hz), 121.42, 119.38, 113.89 (d, J = 10.8 Hz), 108.72 (d, J = 7.6 Hz), 29.69 (d, J = 15.5 Hz), 27.61, 26.24, 23.84 ppm. 31P NMR
Conflicts of interest

There are no conflicts to declare.

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References

22 The pyrrolidine rings of 8 are found to be disordered, but the interior P, N, and C atoms were not.
25 We also prepared analogues of 4 with N-octyl and N-cyclohexyl substituents. Although we did not isolate these compounds, their crude 31P NMR data were consistent with exclusive monomer formation.


