Alleviating Strain in Organic Molecules by Incorporation of Phosphorus: Synthesis of Triphosphatetrahedrane

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Abstract:

Phosphatetrahedranes (^{t}BuCP)$_2$ and (^{t}BuC)$_3$P were recently reported and represent the first tetrahedranes containing a mixed carbon/phosphorus core. Herein, we report that tetrahydrofuran (THF) solutions of the parent triphosphatetrahedrane HCP_3 may be generated in 31% yield (NMR internal standard yield) by combining [Na(THF)$_3$][P$_3$Nb(ODipp)$_3$] (Dipp = 2,6-diisopropylphenyl), INb(ODipp)$_3$(THF), and bromodichloromethane in thawing THF. While HCP_3 was found to be stable in dilute THF solutions for extended periods of time, concentration of the solution at −40 °C led to the formation of a black precipitate, which has been tentatively assigned as a polymerized form of HCP_3. HCP_3 reacts readily with (dppe)Fe(Cp*)Cl (dppe = 1,2-bis(diphenylphosphino)ethane, Cp* = η^5-C$_5$Me$_5$) in the presence of Na[BPh$_4$] to form a purple cationic iron complex of triphosphatetrahedrane (50% yield), which was structurally characterized in a single-crystal X-ray diffraction experiment. Additionally, we present a series of homodesmotic equations analyzed via quantum chemical calculations that suggest triphosphatetrahedrane is the least strained of the mixed C/P phosphatetrahedranes.

Following our recent synthesis of tri-*tert*-butylphosphatetrahedrane (^{t}BuC)$_3$P,[1] with the present work we turn our attention to the assembly of a triphosphatetrahedrane, HCP_3 (**1**), the parent molecule containing a tetrahedral core with three phosphorus atoms and a single carbon.[2] We recognized that this target molecule would likely require the development of a new approach to knitting together the four core atoms, as no analog of the cyclopropenium ion, which was key in the phosphatetrahedrane synthesis as the source of the central triangle of carbon atoms,[1] exists for an all-phosphorus triangle. Seeking to adapt the $[P_3]^{3-}$ transfer methodology originally employed for the synthesis of AsP_3,[3] we began by investigating treatment of anionic niobatriphosphatetrahedrane [Na(THF)$_3$][P$_3$Nb(ODipp)$_3$] (**2**, Dipp = 2,6-diisopropylphenyl) with chloroform, to be the source of a core carbon atom, but found no evidence of reaction between these partners. This then stimulated the development of a new radical pathway for the key initial P–C bond-forming step, as detailed below, in what became a successful approach to triphosphatetrahedrane, HCP_3. The molecule has been shown in a theoretical study to be the lowest energy of all possible HCP_3 isomers.[4]

Considering that P_4 is an excellent radical trap,[5–7] we speculated that P−C bond formation might be achieved by combining **2** with a carbon-centered radical. Indeed, treatment of **2** with the Nb(IV) complex INb(ODipp)$_3$(THF) (**3**), intended to function as a halogen-atom abstractor, and excess chloroform (ca. 10 equiv) generated **1** (Fig. 1), which exhibits a ^{31}P NMR resonance centered at δ −540 ppm that couples to a single hydrogen atom (d, $^2J_{PH}$ = 17.5 Hz). The chemical shift of **1** is in good agreement with other reported phosphatetrahedranes (cf. (^{t}BuC)$_3$P, −488 ppm; (^{t}BuCP)$_2$, −468 ppm; P_4, −520 ppm).[1,8,9] Additionally, gas chromatography-mass spectrometry (GC-MS) analysis of the crude reaction mixture revealed a band corresponding to the molecular weight of HCP_3 (105.9 m/z). Improved conversion was observed when bromodichloromethane (1.05 equiv) was substituted for excess chloroform, delivering **1** as the major product in 31% yield (NMR internal standard yield) according to ^{31}P NMR spectroscopy (Fig. 1). The enhanced reactivity may be attributed to the labile C−Br bond of bromodichloromethane, resulting in more facile halogen-atom abstraction by **3**. Note that HCP_3 was not generated when the reaction was repeated with various trihalomethanes in the absence of complex **3** (S.1.5).

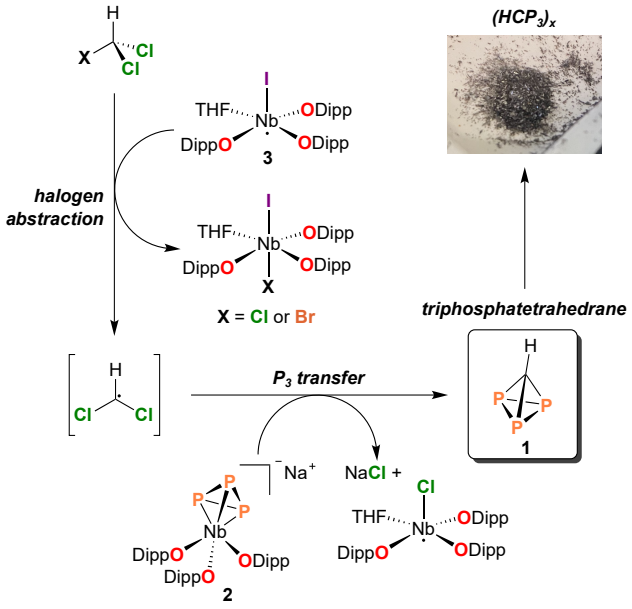

Figure 1. Synthesis of triphosphatetrahedrane (**1**), proposed to proceed through an carbon-centered radical intermediate that is trapped by [Na(THF)$_3$][P$_3$Nb(ODipp)$_3$] (**2**). The radical intermediate is generated by the abstraction of bromine from bromodichloromethane by INb(ODipp)$_3$(THF) (**3**). A polymerized form of HCP_3 was obtained upon concentrating a THF solution of **1** at −40 °C (photograph of black solids).

Consistent with the formation of **1**, integration of the natural abundance ^{13}C satellites ($^1J_{PC}$ = 61.9 Hz) associated with the high-field ^{31}P NMR signal suggests that three equivalent phosphorus atoms are bound to a single carbon atom. Similar to those of (^{t}BuC)$_3$P, the ^{13}C satellites are isotope shifted higher field by ca. 0.03 ppm.[1] Additionally, a quartet centered at 2.94 ppm (THF-d_8) was observed in the ^{1}H NMR spectrum and exhibits a matching $^2J_{PH}$ coupling

constant of 17.5 Hz. A notably large $^1J_{CH}$ coupling constant of 242.2 Hz was observed for **1**, reflecting the high *s* character of the ring C−H bond, and is comparable to that of acetylene ($^1J_{CH} = 249.0$ Hz) [10] and the hydrogen-substituted tetrahedrane $(Me_3SiC)_3CH$ ($^1J_{CH} = 255.6$ Hz) reported by Sekiguchi and co-workers. [11] Using the empirical correlation $^1J_{CH} = 5.70(s\%) - 18.4$ Hz, [12] the *s* character of the C−H bond of **1** is estimated to be 46% ($sp^{1.22}$). Natural bond orbital (NBO) analysis [13] of the optimized structure of HCP_3 (B3LYP-D3/def2-TZVPP) suggest that the C−H bond results from overlap of an $sp^{1.52}$ hybrid on carbon and an *s* orbital on hydrogen, in agreement with the value derived from the empirical correlation.

Compound **1** is volatile and may be separated from the crude mixture by vacuum distillation (200 mTorr) at 22 °C, in addition to THF and halocarbon byproducts. Upon concentration of the distillate at −40 °C under reduced pressure (100 mTorr), a black precipitate forms and loss of the triphosphatetrahedrane ^{31}P NMR resonance is observed (Fig. 1). Note that when the distillate was concentrated, it was protected from ambient light using aluminum foil, suggesting that decomposition of HCP_3 is thermally driven. The black precipitate is insoluble in common organic solvents and elemental analysis reveals that the material is low in carbon and hydrogen (C, 9.19%; H, 0.87%). Powder X-ray diffraction suggests that the black material is amorphous, exhibiting three broad signals between 2θ = 10-25, 30-40, and 55-65°, and broad bands at 2832, 1011, and 657 cm^{-1} are observed in the IR spectrum. It should be noted that the X-ray diffractogram closely resembles that of commercially available amorphous red phosphorus. [14] Interestingly, when a sealed glass capillary containing the black material was placed in a gas flame, a yellow liquid, presumably white phosphorus, condensed on the sides of the capillary and a black solid remained at the bottom of the tube. NMR analysis of the capillary's contents in benzene-d_6 showed clean formation of white phosphorus. Taking these observations into consideration, we have tentatively assigned the black precipitate as a polymer of **1**. Due to its poor stability, we are unable to isolate **1** as a pure substance.

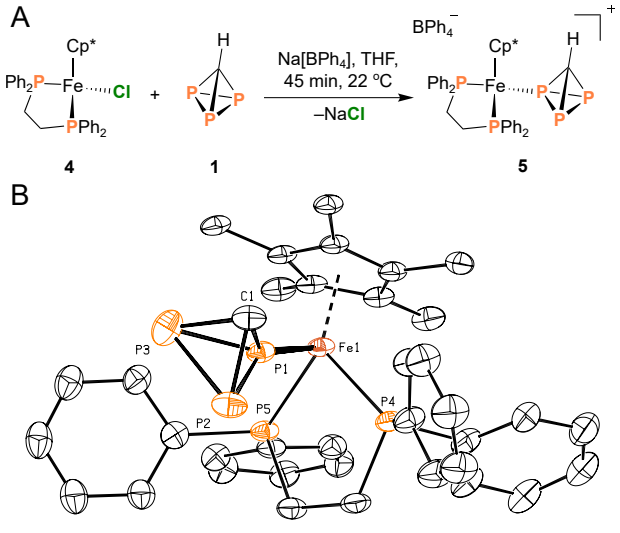

Figure 2. A) Synthesis of [(dppe)Fe(Cp*)(HCP_3)][BPh_4] (**5**). B) Molecular structure of **5** shown with 30% probability thermal ellipsoids. Hydrogen atoms, solvent molecules, and the tetraphenylborate counterion are omitted for clarity.

Complex (dppe)Fe(Cp*)Cl (**4**, dppe = 1,2-bis(diphenylphosphino)ethane, Cp* = η^5-C_5Me_5), which has been shown to form a stable adduct of P_4, [15] reacts readily with concentrated solutions of HCP_3 (ca. 1.7 equiv) in the presence of Na[BPh_4] (1.0 equiv) to form the purple, cationic complex [(dppe)Fe(Cp*)(HCP_3)][BPh_4] (**5**) (Fig. 2A). Complex **5** was isolated as purple crystals in 50% yield by concentrating the reaction mixture under reduced pressure, filtering the solution through Celite, layering the filtrate with diethyl ether, cooling the resulting solution to −30 °C, and collecting the crystals via vacuum filtration. Attempts to further purify the isolated material by recrystallization were unsuccessful due to the poor stability of **5** in solution. Upon redissolving **5** in THF or *ortho*-difluorobenzene, the solution darkens and forms significant amounts of black precipitate, and ^{31}P NMR analysis of the mixture reveals partial decomposition of **5** and formation trace HCP_3. After 12 h at 22 °C in THF, complete decomposition of complex **5** is observed.

Crystals of **5** grown from a mixture of THF and Et_2O at −30 °C were characterized in a single-crystal X-ray diffraction experiment and the molecular structure is depicted in Fig. 2B. This experiment shows that the phosphatetrahedrane is bound to the iron center at a single phosphorus vertex at a distance of 2.1563(15) Å. The P1−Fe1 bond length is notably short, consistent with the high *s* orbital character of the P1 lone pair (cf. 2.208(13) Å and 2.245(16) Å for Fe1−P4 and Fe1−P5, respectively). Additionally, coordination of HCP_3 to the iron center results in distortion of the tetrahedrane, leading to altered C−P bond lengths (P1−C1 1.788(5), P2−C1 1.823(6), P3−C1 1.841(6)). Reflecting this structural perturbation, P1 and P2/P3 exhibit resonances at −316 ppm and −492 ppm in the ^{31}P NMR spectrum, respectively.

Additionally, we found that when (bromodichloromethyl)trimethylsilane is used in place of bromodichloromethane, a high field signal at −520.7 ppm is observed in the ^{31}P NMR spectrum, corresponding to the trimethylsilyl-substituted triphosphatetrahedrane, Me_3SiCP_3. GC-MS and 2D NMR spectroscopic experiments of the crude reaction mixture confirmed the identity of Me_3SiCP_3. However, the conversion for this reaction is only 12%, as assessed by quantitative ^{31}P NMR spectroscopy (S.1.9).

Given our ability to generate the sterically unencumbered parent triphosphatetrahedrane, we evaluated the relative strain enthalpies of P_4, HCP_3, $(HCP)_2$, $(HC)_3P$, and $(HC)_4$ using a series of homodesmotic reactions carried out at the G4MP2 level of theory using Gaussian 09 (Fig. 3). [16–18] A clear trend emerges from this analysis – the incorporation of phosphorus into the tetrahedrane framework alleviates the strain energy of the molecular cage (Fig. 4). This is in agreement with the more diffuse frontier orbitals of heavier p-block elements and the propensity for lone pairs to accumulate *s* orbital character. [19] Consequently, HCP_3 exhibits a modest strain energy of 37.3 kcal/mol, making it the least strained of the mixed C/P phosphatetrahedranes. Additionally, a strain energy of 13.7 kcal/mol was found for P_4, consistent with P_4 being a relatively unstrained molecule. Note that many have confounded the acute bond angles of P_4 with its strain energy, and as a result, chemistry textbooks have erroneously claimed that P_4 is a highly strained molecule. [20–22] Conversely, the parent tetrahedrane $(HC)_4$ exhibits a maximal strain energy of 135.8 kcal/mol; however, despite its significant strain, it is still considered a viable synthetic target. [23]

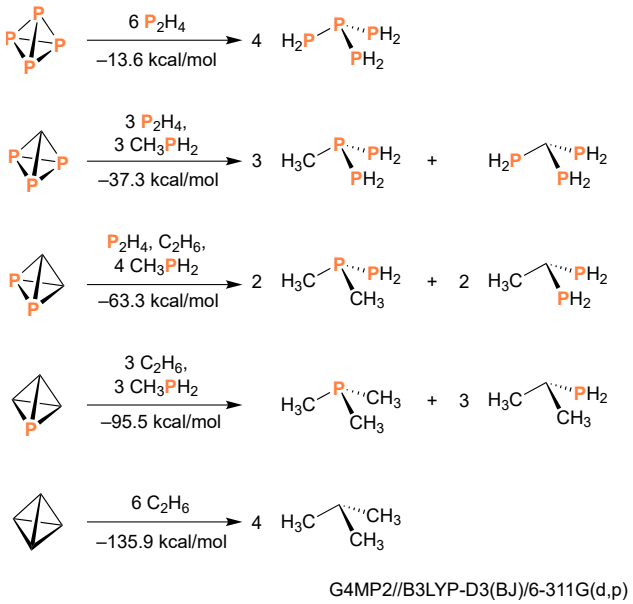

Figure 3. Homodesmotic equations analyzed via quantum chemistry calculations used to determine the strain energies of P_4, HCP_3, $(HCP)_2$, $(HC)_3P$, and $(HC)_4$. All geometries were optimized using the B3LYP-D3(BJ) functional and the 6-311G(d,p) basis set, and strain energies were obtained at the G4MP2 level of theory.

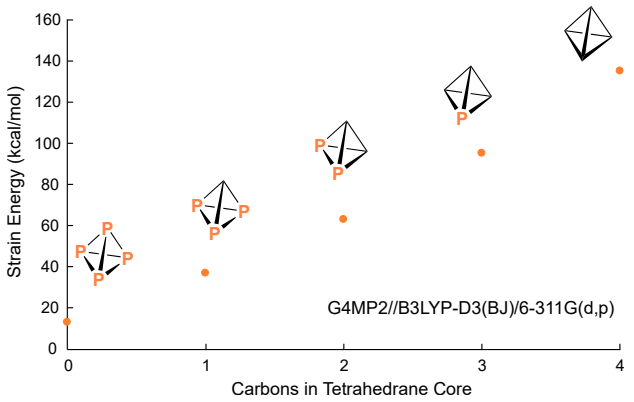

Figure 4. Plot of calculated strain enthalpies of P_4, HCP_3, $(HCP)_2$, $(HC)_3P$, and $(HC)_4$ versus number of carbons in the tetrahedrane core.

In summary, we have described the first synthesis of a tetrahedrane with a core composed of one carbon and three phosphorus atoms. The key C−P bond-forming step is understood in terms of generation and trapping of a carbon-centered radical, generated upon the combination of a Nb(IV) complex and bromodichloromethane, by a metallaphosphatetrahedrane. Considering the rich activation chemistry of P_4, we anticipate that the use of triphosphatetrahedranes as starting materials may facilitate new synthetic routes towards novel organophosphorus compounds. The existence of the new pentaatomic molecule HCP_3, and the metastable black material into which it evolves, provides a vivid illustration that Chemistry has yet to push the boundaries of what is possible when mixing and matching p-block elements and isolobal fragments.

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Supporting Information Available

Crystallographic data are available from the Cambridge Structural Database under refcodes 2092664 and 2092682. Full synthetic and computational details, including preparative procedures and spectroscopic data for characterization of compounds, are in the supplementary materials.

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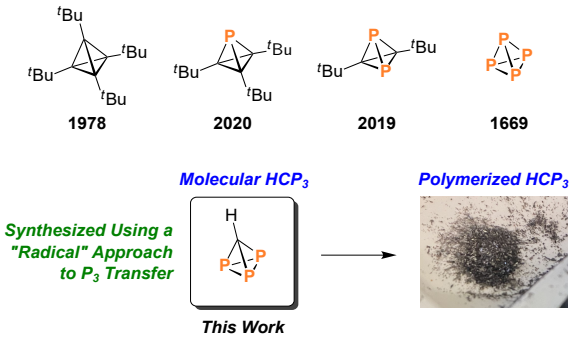
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