Early-Transition-Metal-Mediated Activation and Transformation of White Phosphorus

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Early-Transition-Metal Mediated Activation and Transformation of White Phosphorus

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1 Introduction

Phosphorus-containing molecules are ubiquitous in the world around us and the synthetic and industrial utilization of phosphorus has prospered for over a century.\textsuperscript{1,2} The industrial reduction of phosphate rock (apatite, \(\text{Ca}_{10}(\text{PO}_4)_6(\text{X})_2\), \(\text{X} = \text{OH}, \text{F}, \text{Cl}, \text{or Br}\)) to white phosphorus, \(\text{P}_4\), exceeds 500,000 tons annually as \(\text{P}_4\) still represents the major commercial P-atom source for the production of organophosphorus compounds utilized by the food, detergent, specialty chemical, and pharmaceutical industries.\textsuperscript{3} The present day synthesis of organophosphorus compounds is a multi-step process in which \(\text{P}_4\) is first chlorinated to generate \(\text{PCl}_3\), which in turn is functionalized by reaction with an appropriate Grignard or organolithium reagent, or by treatment with a halogenated organic compound and a powerful reducing agent.\textsuperscript{4,5} For example, the industrial method for triphenylphosphine preparation is based on the high temperature reaction of chlorobenzene with phosphorus trichloride in the presence of molten sodium.\textsuperscript{4,6} From both a safety and a sustainability standpoint, the need for \(\text{PCl}_3\) as an intermediate for the production of organophosphorus compounds is unpalatable and methods that circumvent its use are of great interest. This has provoked intensive investigations into the mild and controlled activation of \(\text{P}_4\), a clear objective being the development of catalytic methods for phosphorus incorporation into organic molecules.
Sustained interest in the chemistry of low-valent, early-transition-metal (ETM) complexes arises from their propensity to reductively activate a wide variety of small molecule substrates. A combination of coordinative unsaturation, inherent Lewis acidity, and availability of chemically accessible $d$ electrons endows low-valent, ETM fragments with a rich reaction chemistry. The ability to apply the reductive power of such reactive metal systems is therefore of great interest for applications ranging from organic catalysis to dinitrogen fixation and it comes as no surprise that low-valent, ETM complexes have received considerable attention as agents for $P_4$ activation. The use of ETM complexes to study $P_4$ activation and functionalization is motivated by the wide array of P-containing ligands that can be obtained. $P_1$ through $P_8$ ligands have been isolated and studied from $P_4$ activation reactions of ETM complexes, and many of these metal-phosphorus systems have proven to be themselves reactive due to the hard-soft mismatch of ETM-phosphorus bonds. This bonding mismatch provides an underlying thermodynamic driving force by which assembled phosphorus ligands can be liberated from the metal center by exchange with preferred hard, anionic ligands, such as $O^{2-}$ and $X^{-}$ ($X = Cl, Br, I$).

The aim of this review is to highlight the wide array of results reported in the literature in the field of $P_4$ activation and transformation with a particular emphasis on the special attributes of ETM utilization in such processes. For the purposes of this work we define “ETM” as any member of groups 3 through 7, and lanthanide and actinide metals are also included for comparison purposes. Sections two through four provide a general overview of the $P_4$ activation chemistry of this group of elements organized in terms of the phosphorus products that result. Section five details the strategies by which ETM chemists have gone about transforming white phosphorus in the coordination sphere of a metal *en route* to the synthesis of main-group phosphorus-containing molecules.
2 P₄ Activation Leading to P₁, P₂, and P₃ Products

ETM-mediated degradation of the white phosphorus tetrahedron to small Pₙ units has been observed frequently, and a variety of the possible P₄ degradation products have been characterized. Typical products include those incorporating a terminal or bridging phosphide (P₃⁻) ligand, bridging diphosphide ligand (P₂⁴⁻), and cyclo-P₃ moieties serving either as terminal P₃₃⁻ ligands or as a μ₂ : η¹, η³ bridge between two metal centers. Few mechanistic studies have been explicitly carried out on these P₄ degradation reactions; mechanistic proposals have been put forward in various cases,⁸,⁹ but these are not included in the coverage of the present review. The focus herein is on synthetic, structural, and spectroscopic details.

2.1 Terminal and Bridging P₁ Ligands from P₄

There are few examples of monophosphorus ligands derived directly from activation of P₄ that have been reported, and all of them involve group 6 metal complexes (Figure 1). The first terminal phosphide complex to be obtained from transition metal activation of P₄ was P≡Mo(N[i'Br]Ar)₃ (1; Ar = 3,5-C₆H₃Me₂).¹⁰ Prior to this report and a concurrent report by Schrock and coworkers on the synthesis of P≡Mo(Me₃SiNCH₂CH₂)₃N and P≡W(Me₃SiNCH₂CH₂)₃N from reaction of the precursor chloro complexes and Li[P(H)Ph],¹¹ the M≡P functional group was virtually unknown.¹²,¹³ Compound 1 was synthesized by Cummins and coworkers by treatment of three-coordinate Mo(N[i'Br]Ar)₃ with 0.35 equiv of P₄ at 25 °C in diethyl ether.¹⁰ Analogous terminal phosphide complexes, P≡Mo(N[i'Br]Ph)₃, 2, and P≡Mo(N[i²Ad]Ar)₃, 3, obtained from reaction of white phosphorus with Mo(N[i'Br]Ph)₃ and Mo(N[i²Ad]Ar)₃, respectively, have also been reported.¹⁴,¹⁵ Interestingly, reaction of Mo(H)(η²-Me₂C=NAr)(N[i'Pr]Ar)₂, a tautomer of Mo(N[i'Pr]Ar)₃, with P₄ does not directly give the terminal P≡Mo(N[i'Pr]Ar)₃, 4, but instead, the bridging (Ar[i'Pr]N)₃Mo=P=Mo(N[i'Pr]Ar)₃, 5, is obtained. This bimetallic complex is likely a result of quenching a transiently formed terminal phosphide complex with an additional equivalent of Mo(H)(η²-Me₂C=NAr)(N[i'Pr]Ar)₂.¹⁶ Complex 4, however, can be revealed by a re-
duction reaction of 5 to give the intact bimetallic complex monoanion followed by treatment with an equivalent of CO and 12-crown-4 with loss of the carbonyl anion salt [Na(12-crown-4)]((OC)Mo(N[1Pr][Ar])₃]. ¹⁶ Outside of the tris-anilide family of complexes, one other example of terminal phosphide formation from P₄ has been reported, and it too stems from a reactive three-coordinate molybdenum complex. Treatment of Mo(OSiᵗBu₃)₃ with 0.35 equiv of P₄ at 23 °C in diethyl ether results in clean formation of P≡Mo(OSiᵗBu₃)₃, ⁶ ¹⁷ Complexes 1, 2, 3, 4, and 6 each display a ³¹P NMR resonance downfield of 1200 ppm. These signature low-field shifts are the result of a strong contribution from the paramagnetic shielding term, the origin of which is electronic circulations arising from field-induced mixing of the M–P σ bonding orbital with the M–P π* orbital. ¹⁸ Structurally characterized molybdenum terminal phosphide complexes display very short Mo≡P interatomic distances, averaging 2.11 Å, in accord with the interpretation that they incorporate a triple-bond functional group (triple bond covalent radius for Mo is 1.13 Å and for P is 0.94 Å). ¹⁹

In a reaction related to P₄ activation by three-coordinate molybdenum, the dimethylamine adduct of the tungsten dimer W₂(OCH₂ᵗBu)₆ was treated with P₄ in toluene at 75 °C with the stated goal of preparing the W≡P functional group. Obtained instead was the complex, (η³-P₃)W(OCH₂ᵗBu)₃(HNMe₂) (vide infra), together with the trimetallic monophosphide complex W₃-(μ₃-P)(μ-OCH₂ᵗBu)₃(OCH₂ᵗBu)₆, ⁷ ²⁰,²¹ It was postulated that ⁷ was formed by trapping of a sterically unprotected and highly reactive P≡W(OCH₂ᵗBu)₃ intermediate by an equivalent of the starting material W₂(OCH₂ᵗBu)₆. ²¹ The phosphide resonance in ⁷ differs markedly from those of the terminal molybdenum phosphide species, consisting of a singlet at 275 ppm flanked by tungsten satellites. In the single-crystal X-ray structure of ⁷, each tungsten atom resides in a square-pyramidal coordination geometry with the W–P bond occupying the axial site (W–P = 2.365(4) Å). The average W–W distance is 2.757(1) Å, and the angles within the distorted W₃P tetrahedron are W–W–W = 60°, W–P–W = 71.3(1)°, and P–W–W = 54.3(1)° (Figure 2). ²¹

The observation of both bridging and terminal monophosphide ligands from P₄ activation by ETM complexes highlights the importance of steric factors in moderating the reactivity of such
Figure 1: Monophosphide ligands derived from P₄ activation; yields given where available.

Figure 2: Structural diversity in monophosphorus ligands derived from P₄ activation.
metal fragments towards \( P_4 \) and emphasizes the integral role of the ancillary ligands in \( P_4 \) activation chemistry. A thorough review of metal terminal phosphides originating from \( P_4 \) and from other \( P \)-containing substrates has been provided by Scheer and coworkers.\(^{12,13}\)

### 2.2 Bridging P\(_2\) Ligands from P\(_4\)

The symmetrical degradation of the \( P_4 \) tetrahedron to \( P_2 \) units often results in diphosphorus ligands bridging two metal centers in a \( \mu_2 : \eta^2, \eta^2 \) coordination mode (Figure 3). Many of the reports involving \( P_2 \) ligands have been documented by Scherer and coworkers. The first diphosphorus-containing metal complex was isolated and characterized in Scherer’s laboratories in 1984. Treatment of the molybdenum dimer \([\text{MoCp(CO)}_2]_2\) with \( P_4 \) in toluene at 110 °C for 8 h gives a mixture of (\( \eta^3\)-\( P_3 \))\( \text{Mo(CO)}_2\)Cp (\emph{vide infra}) and \( \text{Mo}_2(\text{CO})_4\)\( \text{Cp}_2(\mu_2 : \eta^2, \eta^2\)-\( P_2 \)), \( 8 \).\(^{22}\) This chemistry was found also to be available with substituted cyclopentadienyl complexes of Mo, including those containing \( \text{Cp}^* \).\(^{23,24}\) Compound 8 exhibits a side-on bound \( P_2 \) unit with a \( P–P \) interatomic distance of 2.079(2) Å and a short Mo–Mo distance of 3.022(1) Å. It is noteworthy that a common feature of bridging diphosphorus ligands is an incomplete reduction of the \( P–P \) multiple bonding character (relative to the free \( P_2 \) molecule) as signified by \( P–P \) interatomic distances significantly shorter than those for a typical \( P–P \) single bond, for which a typical example is the 2.21 Å \( P–P \) interatomic distance in \( P_4 \).\(^{25}\) This type of transformation was extended to chromium by Goh and coworkers who discovered that treatment of the chromium dimer \([\text{CrCp(CO)}_3]_2\) with \( P_4 \) for 3.5 h at 90 °C in toluene results in a mixture of (\( \eta^3\)-\( P_3 \))\( \text{Cr(CO)}_2\)Cp (\emph{vide infra}) and \( \text{Cr}_2(\text{CO})_4\)\( \text{Cp}_2(\mu_2 : \eta^2, \eta^2\)-\( P_2 \)), \( 9 \).\(^{26}\) Complex 9 exhibits a side-bound \( P_2 \) unit with a \( P–P \) interatomic distance of 2.060(1) Å and a Cr–Cr interatomic distance of 3.011(1) Å.

Since these initial reports, it has been found that a wide range of ETM carbonyl complexes supported by cyclopentadienyl and substituted cyclopentadienyl ligands do indeed give rise to side-on coordinated diphosphorus ligands bridging two transition metal centers in a butterfly format. For example, \([\text{ReCp}^*(\text{CO})_2]_2\) reacts with \( P_4 \) in toluene upon warming a chilled solution to 23 °C to give \( \text{Re}_2(\text{CO})_4\)\( \text{Cp}^*\)\( _2(\mu_2 : \eta^2, \eta^2\)-\( P_2 \)), \( 10 \). Complex 10 adopts an \( M_2P_2 \) butterfly geometry with no
direct metal-metal interaction.\textsuperscript{27} If the reaction mixture leading to 10 is not cooled prior to addition of P\textsubscript{4}, then 10 is formed only in trace quantities with the dominant reaction product being the tetranuclear complex, [Re(CO)Cp\textsuperscript{*}]\textsubscript{4}(P\textsubscript{2}), 11.\textsuperscript{28} This diphosphinidine complex exhibits an unusual P\textsubscript{2} ligand stabilized as a formal 8 σ electron donor. The P–P interatomic distance in 11 is a lengthy 2.226(3) Å, suggesting a P–P bond order of one, as compared with the short 2.032(8) Å interphosphorus distance exhibited by 10. The finding of complex 11 illustrates the versatility of the diphosphorus ligand in being able to stabilize coordination complex clusters having two or more metals. A further example reported by Scherer and coworkers involves the photolytic reaction of Cp’’Ta(CO)\textsubscript{4} (Cp’’ = \textit{η}\textsubscript{5},1,3-C\textsubscript{5}H\textsubscript{3}t\textsubscript{Bu}\textsubscript{2}) with P\textsubscript{4} in toluene at 22 °C giving rise to three products including Cp’’(CO)\textsubscript{2}Ta(\textit{η}\textsubscript{4}-P\textsubscript{4}) (vide infra), (Cp’’(CO)Ta)\textsubscript{2}(\mu\textsubscript{2} : \textit{η}\textsuperscript{2}, \textit{η}\textsuperscript{2}-P\textsubscript{2})\textsubscript{2}, 12, and (Cp’’(CO)Ta)\textsubscript{3}(\mu\textsubscript{2} : \textit{η}\textsuperscript{2}, \textit{η}\textsuperscript{2}-P\textsubscript{2})\textsubscript{2}, 13, in low yield.\textsuperscript{29} Complex 12 was structurally characterized and found to contain short P–P interatomic distances (2.120(3) Å) in the coordinated diphosphorus ligands. No interaction between the two diphosphorus units was observed.

Cyclopentadienyl-supported ETM hydride complexes have also been shown to be viable reaction partners with P\textsubscript{4} leading to coordinated parent diphosphene, HP=PH, ligands resulting from transfer of hydride from the metal center to phosphorus. An early example of this type of transformation was provided by Green and coworkers who showed that treatment of the dihydride complex Cp\textsubscript{2}MoH\textsubscript{2} with an excess of P\textsubscript{4} in toluene at 90 °C leads to the red complex Cp\textsubscript{2}Mo(HP−−PH), 14.\textsuperscript{30} Subsequently, this compound was characterized crystallographically by Canillo \textit{et al.}\textsuperscript{31} These reports were followed much later by the report by Stephan and coworkers of similar insertion behavior for the related trihydride complex Cp\textsubscript{2}TaH\textsubscript{3}. Specifically, it was found that treatment of Cp\textsubscript{2}TaH\textsubscript{3} with white phosphorus overnight at 85 °C in toluene elicits formation of Cp\textsubscript{2}TaH(HP−−PH), 15.\textsuperscript{32}

In addition to cyclopentadienyl-supported ETM complexes, the reactive niobaziridine hydride complex, Nb(H)(\textit{η}\textsuperscript{2}-Bu(H)C=NAr)(N[CH\textsubscript{2}t\textsubscript{Bu}]Ar)\textsubscript{2}, has also been shown to give a coordinated P\textsubscript{2} ligand upon reaction with white phosphorus. Treatment of the niobaziridine hydride complex with P\textsubscript{4} in diethyl ether gives rise quantitatively to (\mu\textsubscript{2}:\textit{η}\textsuperscript{2},\textit{η}\textsuperscript{2}-P\textsubscript{2})[Nb(N[CH\textsubscript{2}t\textsubscript{Bu}]Ar)\textsubscript{3}]\textsubscript{2}, 16.\textsuperscript{33} This
Figure 3: Bridging and side-on bound diphosphorus ligands derived from P₄ activation; yields given where available.

Figure 4: Structural diversity in diphosphorus ligands derived from P₄ activation.
reaction was found to be insensitive to the reaction conditions used, giving rise to 16 regardless of the P:Nb stoichiometry. The reaction can be viewed as a 2e per Nb reduction of the P₄ tetrahedron and is reminiscent of the mild activation of P₄ reported for the molybdenum(III) tris-amide system discussed above.¹⁰ Compound 16 displays the typical M₂P₂ butterfly geometry seen for coordinated diphosphorus units with a short P–P interatomic distance of 2.150(2) Å and no direct metal-metal interaction. The molecular structure of 16 is shown in Figure 4 along with examples of other molecular geometries for coordinated P₂ ligands.

Recently, two examples of a rare end-on coordination mode for a P₄-derived diphosphorus ligand have been observed by Wolczanski and coworkers, these being demonstrated as a bridging component spanning a pair of three-coordinate niobium or tantalum metal fragments.³⁴ Treatment of Ta(OSi′Bu₃)₃ with P₄ in toluene gives rise to (µ₂:η¹⁻¹-P₂)(Ta(OSi′Bu₃)₃)₂, 17. Interestingly, reaction of the related PMe₃-stabilized Nb(OSi′Bu₃)₃ with P₄ gave different major products depending upon the reaction conditions. When the reaction was run at 23 °C in toluene, the purple (µ₂:η¹⁻¹-P₂)(Nb(OSi′Bu₃)₃)₂, 18, could be isolated in 70% yield. However when the reaction mixture was kept at −78 °C for 7 h prior to warming to room temperature, the red hexaphosphorus complex (µ₂:η²⁻²-P₆)(Nb(OSi′Bu₃)₃)₂ could be isolated in good yield (vide infra). Complex 17 proved isomorphous to 18, with both species displaying an end-on zig-zag coordination mode for the M₂P₂ core. The P–P interatomic distances in 17 and 18 are slightly longer than those of the P₂ complexes discussed previously, at 2.171(2) and 2.143(1) Å, respectively; the structural features point to a diphosphinidene, i.e. M=P–P=M, Lewis picture for these systems that incorporates metal-phosphorus double bond character. It is presumed that the end-on coordination observed in 17 and 18 may be due to the steric pressure provided by the bulky OSi′Bu₃ ligands surrounding the metal centers. To date, simple 1:1 complexes of a transition metal with a P₂ ligand have not been observed and remain sought-after targets.
2.3  *Cyclo*-P$_3$ Units derived from P$_4$

The activation of P$_4$ in the coordination sphere of a metal complex to give a triphosphorus unit has been observed frequently, often as a pathway that competes with formation of a monophosphide complex.$^8$ Triphosphorus ligands derived from P$_4$ appear generally as *cyclo*-P$_3$ units that bind to a metal in an η$^3$ coordination mode. Sacconi and coworkers have provided the field with many examples of *cyclo*-P$_3$ ligands crowning various transition metal centers, including the first structurally characterized example in both the terminal disposition (in a cobalt system) and as a symmetrical μ$_2$ : η$^3$, η$^3$ ligand connecting two nickel centers.$^{35}$ Much of this seminal late-metal work has been reviewed elsewhere.$^{8,36-38}$

The earliest *cyclo*-P$_3$ complexes in an ETM context were isolated as coproducts of P$_4$ activation chemistry. For example, the complexes (η$^3$-P$_3$)Mo(CO)$_2$Cp, 19, and (η$^3$-P$_3$)Cr(CO)$_2$Cp, 20, were isolated from product mixtures that resulted when the parent dimer complexes [Cp(CO)$_2$Mo]$_2$ and [Cp(CO)$_3$Cr]$_2$ were treated with P$_4$ in hot toluene solutions (Figure 5).$^{22,26}$ Similarly, Chisholm et al. found that treatment of the dimethylamine adduct of the tungsten dimer W$_2$(OCH$_2$'Bu)$_6$ led to a trimetallic monophosphide cluster together with the *cyclo*-P$_3$ complex (η$^3$-P$_3$)W(OCH$_2$'Bu)$_3$, 21, as a minor product.$^{20}$

![Cyclo-P$_3$ complexes](image)

Figure 5: *Cyclo*-P$_3$ ligands derived from P$_4$ activation; yields given where available.
Masked metal(III) (M = Cr, Mo, W) derivatives have been found to produce cyclo-P₃ complexes upon activation of white phosphorus. For instance, Mo(H)(η²-Me₂C=NAr)(N[iPr]Ar)₂ (a tautomer of Mo(N[iPr]Ar)₃) reacts with P₄ to provide the µ-phosphide complex 5 in high yield (vide supra); this is the main reaction channel when diethyl ether, in which P₄ is not very soluble, is used as the solvent. However, upon adding a toluene solution of the molybdaziridine hydride complex Mo(H)(η²-Me₂C=NAr)(N[iPr]Ar)₂ to a toluene solution containing excess P₄, the cyclo-P₃ complex (η³-P₃)Mo(N[iPr]Ar)₃, 22, is favored as the reaction product.⁹

A recent addition to the family of cyclo-P₃ complexes derived from P₄ is the anionic niobium complex, [(η³-P₃)Nb(ODipp)₃]⁻ (23, Dipp = 2,6-diisopropylphenyl, Figure 6). The complex anion 23 forms upon reduction of Cl₂Nb(ODipp)₃ with an excess of 0.5% sodium amalgam in the presence of 1 equiv of P₄ in THF.³⁹ The negative charge associated with this cyclo-P₃ complex evidently imparts it with nucleophilic character at phosphorus and thus leads to enhanced reactivity as compared with neutral group 6 metal-P₃ complexes (vide infra).

Figure 6: Structural diversity in cyclo-P₃ ligands derived from P₄ activation.

There are several unifying features to the small family of ETM terminal cyclo-P₃ complexes. The ³¹P NMR resonance that is characteristic of cyclo-P₃ complexes coordinated to transition metals is a singlet found between −180 and −220 ppm. Such a high-field shift is characteristic of polyphosphorus units with small endocyclic bond angles, as found in a P₃ ring.⁴⁰ Structurally, each of the above-mentioned cyclo-P₃ complexes displays a symmetrical P₃ unit that can reasonably be
viewed as a $P_3^{3-}$ ligand. It should be noted that the P–P interatomic distances for structurally characterized $P_3$ complexes are not invariant. For instance, 20 and 21 both display somewhat short average P–P interatomic distances of 2.12 and 2.15 Å, respectively. The anionic complex 23, on the other hand, displays average P–P interatomic distances of 2.20 Å, which are much closer to those found for the P–P single bonds of $P_4$ (2.21 Å), but this may be due to interaction of the $P_3$ ring with a sodium counter-cation in the solid state. Such ostensible elongation of the P–P distances in a cyclo-$P_3$ ring is also observed for bimetallic $P_3$ complexes. Cyclo-$P_3$ as a bridging ligand is rare within the ETM regime, though examples do exist. For example, treatment of $Cp''_2Th(\eta^4-\text{C}_4\text{H}_6)$ with $P_4$ in the presence of 0.5 equiv of MgCl$_2$(OEt$_2$) in toluene at 100 °C for 20 h was reported to give the asymmetric bimetallic complex $Cp''_2Th(\mu_2:\eta^3,\eta^3-P_3)Th(\text{Cl})Cp''_2$, 24 (Figure 6). The average P–P distance in 24 was found to be 2.185 Å.

3  $P_4$ Activation Leading to $P_4$ Products

There is wide interest in understanding the nature of the metal-$P_4$ interaction that precedes the P–P bond activation chemistry that is typically observed upon reaction of transition-metal complexes with white phosphorus. In most instances where $P_4$ is observed to react with a transition metal complex, the integrity of the $P_4$ tetrahedron is not maintained and fragmentation and/or aggregation processes transpire. In some cases, the four atoms of the $P_4$ tetrahedron are each incorporated into the metal complex product affording derivatives containing tetraphosphabicyclobutane, tetraphosphabutadiene, or cyclo-$P_4$ coordination. In contrast, there are relatively few known coordination compounds featuring an intact $P_4$ tetrahedron. The earliest report of $P_4$ as a coordinated ligand on a transition metal was provided by Ginsberg and Lindsell in 1971 with the synthesis of $(P_4)Rh(PPh_3)_2\text{Cl}$, though the mode of coordination was not initially ascertained due to the lack of crystallographic or conclusive NMR analysis. The latter data were not reported until 1986 and were suggestive of an open edge, where a tetraphosphabicyclobutane coordinates to a metal(III) center. Sacconi deserves credit for the first full characterization of an intact tetraphosphorus
ligand coordinated to a metal complex. His research group found that treatment of a nickel(0) complex, \( \text{Ni(np}_3) \) \((\text{np}_3 = \text{N(C}_2\text{H}_4\text{PPh}_2)_3)\), with \( \text{P}_4 \) in THF gave rise to the complex \((\text{P}_4)\text{Ni(np}_3)\) with the \( \text{P}_4 \) unit bonded to the metal atom by an apical \( \text{P} \) atom in an \( \eta^1 \) fashion.\(^{46}\) Two years later Sacconi’s group provided the second well-characterized example of a tetrahedro tetraphosphorus ligand, this time on Pd and supported by the related triphos ligand \((\text{triphos} = \text{MeC(CH}_2\text{PPh}_2)_3)\).\(^{47}\) The chemical literature possessed these two as its only examples of an intact \( \text{P}_4 \) tetrahedron serving as a 2e ligand atop a transition metal complex for over twenty years despite a surge in the study of \( \text{P}_4 \) activation chemistry.

### 3.1 Coordination of \( \text{P}_4 \) Tetrahedra

The first reports of the coordination of intact \( \text{P}_4 \) molecules to an ETM center came in 1998 from Scheer and coworkers. They found that the electronically and coordinatively unsaturated compounds \( \text{M(CO)}_3(\text{PR}_3)_2 \) \((\text{M} = \text{Mo, W}; \text{R} = \text{iPr, Cy})\), can serve as starting materials for coordination of the \( \text{P}_4 \) tetrahedron.\(^{48,49}\) Slow addition of \( \text{P}_4 \) to a toluene solution of \( \text{M(CO)}_3(\text{PCy}_3)_2 \) at \(-78^\circ\text{C}\) followed by warming to \(-20^\circ\text{C}\) gives orange \( \text{M(CO)}_3(\text{PR}_3)_2(\eta^1-\text{P}_4) \) \((\text{M} = \text{Mo, R} = \text{Cy, 25}; \text{M} = \text{W, R} = \text{Cy 26}; \text{M} = \text{Mo, R} = \text{iPr 27, Figure 7})\). Complexes 25, 26, and 27 decompose in solution above \( 0^\circ\text{C} \), but are stable as solids under argon at ambient temperatures.\(^{49}\) Next, an example of an intact \( \text{P}_4 \) tetrahedron coordinated to an ETM came from the group of Peruzzini and in that report an intact \( \text{P}_4 \) ligand was observed as both a terminal and as a bridging entity.\(^{50}\) The complex \((\text{triphos})\text{Re(CO)}_2(\text{OTf})\), containing a weakly coordinated triflate ligand, was treated with a small excess of \( \text{P}_4 \) at \( 35^\circ\text{C} \) and was found to give, after work-up, the mustard colored \([((\text{triphos})\text{Re(CO)}_2(\eta^1-\text{P}_4))][\text{OTf}]\), \( 28 \), in good yield.\(^{50}\) Additionally, it was found that the “distal” \( \text{P}_3 \) face of the tetrahedro-\( \text{P}_4 \) ligand still maintained reactivity towards unsaturated transition-metal complexes and electrophiles. Accordingly it was revealed that treatment of 28 with an additional equivalent of \((\text{triphos})\text{Re(CO)}_2(\text{OTf})\) resulted in formation of the bimetallic complex, \([((\text{triphos})\text{Re(CO)}_2(\mu_2:\eta^1,\eta^1-\text{P}_4))][\text{OTf}]_2\), 29, which contains an intact \( \text{P}_4 \) tetrahedron and is the first report of such a ligand serving as a bridge between two metal centers.
Figure 7: Intact and rearranged P₄ ligands derived from P₄ activation; yields given where available.
3.2 Rearranged P₄ Products

Rearranged P₄ units have also been observed as ligands attached to early transition metals; these ligands can display various geometries including the tetraphosphabicyclobutane and the cyclo-P₄ coordination modes. The reaction pathways that generate the various types of P₄ ligands have been speculated upon, but detailed mechanistic studies are essentially nonexistent.⁸

The structural motif involving the fewest bond cleavage events from intact P₄ is the tetraphosphabicyclobutane geometry (butterfly geometry). Only three examples of ETM P₄-butterfly complexes have been reported. Scherer and coworkers found that treatment of Cp₂”M(CO)₂ (M = Zr, Hf; Cp” = η⁵-1,3-C₅H₃(Bu₂) with P₄ in refluxing xylene resulted in oxidative addition of the P₄ tetrahedron and clean formation of the air-stable complexes Cp₂”M(κ²-P₄) (M = Zr, 30; M = Hf, 31).⁵¹ More recently, Chirik et al. reported on formation of a similar Zr product, Cp*₂Zr(κ²-P₄) (32), which they obtained by treatment of Cp₂*Zr(H)₂ with P₄ in toluene at −35 °C.⁵² Surprisingly, Chirik and coworkers also found that treatment of the related dihydride Cp*⁶(C₅H₄'Bu)Zr(H)₂ with P₄ under the same reaction conditions did not lead to the tetraphosphabicyclobutane structure, but instead to (Cp*(η⁵-C₅H₄'Bu)Zr(H)₂(μ₂:η²,η²-P₄H₂), 33.⁵² The phosphorus core of 33 is best viewed as a (P₄H₂)⁴⁻ fragment resulting in two formally 16-electron Zr(IV) centers, and may be considered as a rare example of a hydrogenated P₄⁴⁻ ligand (Figure 8). A related example of formation of a P₄ chain with concomitant functionalization has been provided by Lappert and coworkers who found that treatment of Cp₂Zr(P(SiMe₃)₂)₂ with P₄ in toluene at 20 °C results in P–P bond scission, phosphido-migration, and intramolecular rearrangement to yield the zircona(tetraphospha)bicyclo[2.1.0]pentane complex Cp₂Zr(η¹,η¹-P₄-P(SiMe₃)₂), 34, where the P(SiMe₃)₂ units are bonded to the two peripheral P atoms.⁵³

By 1989, of the possible cyclo-Pₙ compounds isoelectronic to the carbocyclic π systems, x = 3 – 6, only cyclo-P₄ had not been reported. It was in that year that Scherer reported the photochemical synthesis of the first examples of cyclo-P₄ ligands. Irradiation of Cp*⁶Nb(CO)₄ in the presence of P₄ in hexane solution at room temperature gave rise to a mixture of products including Cp*(CO)₂Nb(η⁴-P₄) (35), (Cp*(CO)Nb(μ₂:η²-P₂))₂, and (Cp*⁶Nb)₂(P₆) (vide infra).⁵⁴
The phosphorus NMR spectrum of 35 at room temperature consists of a broad singlet; at 223 K, this resonance splits into the well-resolved signals of an AMX$_2$ spin system, suggestive of hindered rotation of the cyclo-P$_4$ ligand. The bonding in this system may be formally considered as a P$_4^{2-}$ ring which consists of an allyl-like P$_3^-$ monoanion and a phosphido-like anion. Alternative, more symmetric bonding descriptions for cyclo-P$_4$ ligands include a neutral bis(diphosphene) ligand and a P$_4^{4-}$ tetraphosphido ligand, but the bond lengths and NMR data for this particular compound are most consistent with the allyl-phosphido description. Similar reactions have been observed for vanadium to give Cp$^\#$(CO)$_2$V($\eta^4$-P$_4$) (36), and with tantalum to give Cp$^\#$(CO)$_2$Ta($\eta^4$-P$_4$) (37).\textsuperscript{29,55}

The photochemical reaction of P$_4$ with group 6 metal carbonyl complexes has also been used to access cyclo-P$_4$ complexes. Dahl and coworkers discovered that irradiation of THF solutions of W(CO)$_6$ and P$_4$ gave rise to W(CO)$_4$(\eta$^4$-P$_4$)(W(CO)$_5$)$_4$, 38, in 67% isolated yield.\textsuperscript{56} Similarly, Scheer \textit{et al.} found that the photochemical reaction of (Cp’Mo(CO)$_3$)$_2$ (Cp’ = \eta$^5$-C$_5$H$_4$’Bu) with white phosphorus in the presence of Cr(CO)$_5$(THF) leads to a mixture of Cr(CO)$_4$(\eta$^4$-P$_4$)(Cr(CO)$_5$)$_4$ (39), Cp’Mo(CO)$_2$(\eta$^3$-P$_4$)(Cr(CO)$_5$)$_4$(H) (40), and the diphosphorus complex (Cp’Mo(CO)$_2$)$_2$(\mu$_4$:\eta$^2$-P$_2$)(Cr(CO)$_5$)$_2$.\textsuperscript{57} A further example of cyclo-P$_4$ ligand formation has been provided by Fryzuk and coworkers using a zirconium diamidodiphosphine macrocycle complex. They found that treatment of ZrCl$_2$(P$_2$N$_2$) (P$_2$N$_2$ = PhP(CH$_2$SiMe$_2$NSiMe$_2$CH$_2$)$_2$PPh) with P$_4$ and 4 equiv of KC$_8$ in toluene gave rise to the $D_{2d}$ symmetric bridging cyclo-P$_4$ complex (Zr(P$_2$N$_2$))$_2$(\mu$_2$:\eta$^4$,\eta$^4$-P$_4$) (41).\textsuperscript{58} The P$_4$ unit in 41 is nearly a perfect square and can be considered as a P$_4^{4-}$ ligand.
A further example of a cyclo-P$_4$ ligand is found sandwiched between two uranium metal centers. It was found that treatment of (THF)U(N[′Bu]Ar)$_3$ with 0.5 equiv of P$_4$ results in clean formation of ($\mu_2$:\(\eta^4,\eta^4\))-P$_4$[U(N[′Bu]Ar)$_3$]$_2$, 42, which displays a singlet in its phosphorus NMR spectrum at 794 ppm. The square tetraphosphorus bridge in compound 42 represents the formal two-electron reduction of P$_4$ with concomitant formation of two U(IV) fragments. Compound 42 crystallizes in the space group P$\overline{1}$, and the two halves of the molecule are related by an inversion center located at the P$_4$-square centroid. Density functional theory calculations show that the HOMO-1 orbital in 42 has $\delta$ symmetry but there is minimal overlap between the bridging ligand and the two metal centers. As no other orbitals show appreciable overlap between the uranium centers, 42 is formulated as an ionic compound supported by a weak $\delta$ bond.

4 P$_4$ Activation Leading to P$_{\geq 5}$ Products

The divergent and fascinating reactivity of P$_4$ with ETM systems is highlighted particularly well by the cases in which polyphosphorus ligands with greater than four P atoms are formed. Instances of such aggregation are common in P$_4$ activation chemistry and these reactions are important to developing a thorough understanding of structure and bonding in phosphorus chemistry. Perhaps one of the most intriguing examples of P$_4$ activation by an ETM was provided by Ellis and coworkers in 2002. A highly reactive naphthalene-stabilized titanate complex was first formed by reduction of TiCl$_4$(THF)$_2$ with six equiv of potassium naphthalenide in THF at 260 °C, followed by addition of 2 equiv of 18-crown-6. The complex so obtained was found to react with 2.5 equiv of P$_4$ to give [K(18-crown-6)]$_2$[Ti(\(\eta^5\)-P$_5$)$_2$], 43, an all-inorganic analogue of the titanocene dianion (Figure 9). Despite being isovalent with the group 6 metallocenes, 43 is both surprisingly air and moisture stable and chemically inert. This decaphosphametallocene remains the only such molecule and is a prime example of the isolobal analogy between P atoms and CH fragments.

Both monocyclic and bicyclic P$_6$ ligands have been isolated when sandwiched between early transition metals. The first example of the cyclo-P$_6$ ligand was provided by Scherer and cowork-
Figure 9: P–P aggregation products from P₄ activation; yields given where available.
ers while exploring the chemistry of \([\text{Cp}^\ast(\text{CO})_2\text{Mo}]_2\) with \(\text{P}_4\) as mentioned above. Treatment of \([\text{Cp}^\ast(\text{CO})_2\text{Mo}]_2\) with \(\text{P}_4\) in xylene at 140 \(^\circ\)C results in formation of a mixture of products including the \(\text{Cp}^\ast\) analogues of 8 and 19, as well as the triple-decker complex \([\text{Cp}^\ast\text{Mo}]_2(\mu_2:\eta^6,\eta^6-\text{P}_6)\), 44.\(^{23}\) As the all-phosphorus analogue of benzene, \(\text{cyclo-P}_6\) has been stabilized by a variety of triple-decker complexes of early transition metals including those of W (45), V (46), Nb (47, 48), and Ti (49) by thermolysis of a half-sandwich precursor (usually a cyclopentadienyl/carbonyl complex) with \(\text{P}_4\) in a hydrocarbon solvent.\(^{54,62–65}\) Several of the \(\text{P}_6\) triple-decker complexes adopt the expected \(D_{6h}\) configuration with a planar \(\text{P}_6\) unit, but in the case of 49 a distortion to a chair-like \(\text{cyclo-hexaphosphido}\) form occurs, and the \(\text{P}_6\) ligand binds in a \(\mu_2:\eta^3,\eta^3\) fashion as a \(\text{P}_6^-\) ligand.

Several different geometries can be obtained for \(\text{P}_6\) ligands as illustrated by the activation of \(\text{P}_4\) by \(\text{Cp}^\ast_2\text{Th}(\eta^4-\text{C}_4\text{H}_6)\) in toluene at 100 \(^\circ\)C. The resultant \((\text{Cp}^\ast_2\text{Th})_2(\mu_2:\eta^3,\eta^3-\text{P}_6)\) complex (50) contains a bicyclic \(\text{P}_6^4^-\) ligand, which resembles a reduced hexaphosphabenzvalene ligand sandwiched between two thorium metal centers (Figure 10).\(^{41}\) Yet another unique \(\text{P}_6\) ligand geometry has been provided by Wolczanski and coworkers who found that if a reaction mixture containing \((\text{tBu}_3\text{SiO})_3\text{NbPMe}_3\) and \(\text{P}_4\) was allowed to incubate at \(-78 \, ^\circ\)C for 7 h, followed by slow warming to 23 \(^\circ\)C, then the red \(\text{P}_6\)-complex, \((\text{tBu}_3\text{SiO})_3\text{Nb}(\mu_2:\eta^2,\eta^2-\text{cP}_3-\text{cP}_3)\), 51, could be isolated in 77% yield.\(^{34}\) In 51, two of the niobium-phosphorus distances of 2.559(8) and 2.576(5) \(\text{\AA}\) are sig-
nificantly shorter than the third (2.784(7) Å). The average P–P interatomic distance within each of the \( \text{cP}_3 \) rings is 2.172(2) Å. The two \( \text{cP}_3 \) rings are linked via a 2.217(7) Å diphosphorus bond, thus the parameters may be best represented by considering the interaction as that of a niobium center interacting with a triphosphirene ring and benefiting from substantial backbonding.

Polyphosphorus ligands up through \( \text{P}_{12} \) have been isolated by activation of white phosphorus by late transition-metal fragments, but ETM systems to date have given ligands containing only up to as many as eight phosphorus atoms.\(^8\) Two examples of \( \text{P}_8 \) ligands have been isolated in multimetallic arrangements with early transition metals. Cossairt and Cummins found that when 2 equiv of \( \text{P}_4 \) were combined with \( \text{INb(OC\{2\text{-Ad\}Mes)}_3 \) in a weakly-coordinating solvent, a disproportionation reaction took place producing 0.5 equiv of \( \text{I}_2\text{Nb(OC\{2\text{-Ad\}Mes)}_3 \) and the octaphosphorus complex \( \text{Mes\{2\text{-Ad\}CO}}_3\text{Nb=P(P}_7\text{)Nb(OC\{2\text{-Ad\}Mes)}_3 \), \( \text{52} \).\(^66\) The \( \text{P}_8 \) core of \( \text{52} \) is closely related to that revealed by Wright and coworkers for the product of activation of \( \text{P}_4 \) by \( \text{[(18-crown-6)K]}\text{[Si(SiMe}_3\text{)_3]} \).\(^67\) What distinguished the octaphosphorus cluster in \( \text{52} \) from other related structural motifs seen in polyphosphorus ligands derived from \( \text{P}_4 \) was the fact that it incorporated a metal–phosphinidene bond, the reactivity of which was exploited, in one instance through phospha-Wittig chemistry.\(^61\) Another example of ostensible \( \text{P}_4 \) dimerization comes from the lab of Roesky and coworkers who found that diffusion of \( \text{P}_4 \) vapor into a toluene solution of solvate-free permethyl samarocene, \( \text{Cp}^*\text{Sm} \), over a period of several days resulted in the formation of \( \text{(Cp}^*\text{Sm})_4\text{P}_8 \) (\( \text{53} \)) as red crystals.\(^68\) Complex \( \text{53} \) can be described as containing a \( \text{P}_8^{4-} \) ligand in a realgar-type homoatomic conformation supported by four Sm(III) metal centers and represents the first example of a lanthanide-supported polyphosphe.

## 5 Functionalization and Transfer Methodologies

Much of the reaction chemistry of molecules derived from \( \text{P}_4 \) activation has remained confined to the protective coordination sphere of the metal complex; however, it is becoming increasingly evident that the transfer of such ligands is chemically feasible. While much research has been
targeted at the direct incorporation of $N_2$-derived nitrogen atoms into main group molecules, the analogous chemistry with elemental phosphorus has been explored far less.\textsuperscript{69–74} The incorporation of $P_4$-derived phosphorus atoms into organic frameworks by P-atom transfer reactions mediated by transition-metal complexes could circumvent the need for $PCl_3$ as an intermediate in the synthesis of organophosphorus molecules and open up a wide variety of new methodologies for main-group molecule synthesis.\textsuperscript{75,76} There are limited examples of such methods reported to date, however this reaction base is continually expanding. It is the goal of this section to review the functionalization and, where available, transfer chemistry of $P_4$-derived phosphorus ligands from ETM platforms.

5.1 Functionalization and Subsequent Reactivity of Terminal Monophosphide and Bridging Diphosphorus Complexes Derived from $P_4$

The reason for the late development of the $M\equiv P$ functional group lies in the high reactivity of these triple bonds, which exhibit “side-on” as well as “end-on” reactivity.\textsuperscript{13} Thus, before 1995, highly reactive intermediates containing a metal-element triple bond were the subject of much speculation.\textsuperscript{12,13,20} Unfortunately, the stable terminal phosphide ligands that have been isolated via $P_4$ activation chemistry have the common feature of kinetic stabilization by protection of the triple bond through the use of bulky organic substituents which shut down most “side-on” reactivity of the multiple bond.\textsuperscript{77} One exception to this has been the reaction of $P\equiv Mo(N[Pr]Ar)_3$ with $AdC\equiv P$ to afford the $(cyclo-AdCP_2)Mo(N[Pr]Ar)_3$ complex, \textsuperscript{54} that is the product of combining an $M\equiv P$ triple bond with a $C\equiv P$ triple bond.\textsuperscript{78} It has also been shown that the same $P_4$-derived
terminal phosphide complex, 4, will undergo clean ligand exchange reactions with alcohols to
afford alkoxy-supported terminal phosphide complexes. The fact that the Mo≡P triple bond
remains intact during these transformations is remarkable as the steric protection at the metal center
is reduced greatly in the ensuing alkoxide complexes. In one example, alcoholysis of 4 with
1-adamantanol affords P=Mo(OAd)_3, which itself undergoes “side-on” dimerization to afford a
bridging P_2 complex augmented by a Mo–Mo bond. Such terminal phosphide dimerization with P–
P bond formation and reduction of the metal oxidation state is reminiscent of similar dimerization
pathways that have been observed for group 8 metal nitrido systems, leading to bridging dinitrogen
complexes. The concept of using ligand substitution in a post-P_4 activation step to open up
new synthetic access to phosphide systems deserves more exploration.

The “end-on” reactivity of sterically protected terminal phosphides began to be demonstrated
concomitant with their earliest isolation and structural characterization. The molybdenum complex
1 was shown early on to react with MesN_3 as well as S_8 and ethylene sulfide to afford the termi-
nally functionalized complexes (EP)Mo(N[t-Bu]Ar)_3 (E = MesN, 55; S, 56). In another oxidation
of the terminal phosphide ligand, 1 was oxidized with a solution of dimethyldioxirane in acetone
to the purple terminal PO complex (OP)Mo(N[t-Bu]Ar)_3, 57 (Scheme 1). Complex 57 is the only
documented example of a molecule that contains a terminal PO substituent, and the chemistry of
the M=P=O functional group has been explored only to a limited extent. What is known is that
the phosphoryl phosphorus in the PO complex is susceptible to nucleophilic attack. Complex 57
undergoes a facile reaction with Cp_2ZrMe_2 to afford Cp_2ZrMeOP(Me)Mo(N[t-Bu]Ar)_3, in which
a Zr–O bond has been formed and a methyl group transferred to the P center. More recently,
Piro and Cummins reported that 57 undergoes an O-for-PSiR_3 metathesis reaction with the nio-
bium phosphinidene complex Pr_3SiP=Nb(N[CH_2t-Bu]Ar)_3 to generate the oxoniobium complex
ONb(N[CH_2t-Bu]Ar)_3 and the unusual diphosphenido complex Pr_3SiP=PMo(N[t-Bu]Ar)_3, 58, that
contains a “singly bent” diphosphenido moiety.

The reactivity of the P_2 functional group derived from P_4 activation has been explored to
a reasonable extent and has led to the synthesis of a variety of new molecules. For example,
Scherer and coworkers have discovered that treatment of the dirhenium-P₂ complex 10 with excess W(CO)₅(THF) leads to two new products (Scheme 2). The first isolated product is (Re(CO)₂Cp*)₂-(P₂W(CO)₄), 59, the first example of the transformation of an M₂P₂ butterfly complex to a complex with an M₂P₂ tetrahedrane framework. The second product of this reaction is a tetrametallic species, ((Re(CO)₂Cp*)PW(CO)₄)₂ (60), where the P–P bond has been broken with formation of new W–P and W–W bonds.²⁸ Complex 60 is notable for its downfield ³¹P NMR chemical shift of 885 ppm as well as for its planar six-atom framework for the Re₂P₂W₂ core.

Another striking example of the reactivity of P₂ units was demonstrated by Scheer and coworkers with 9. They discovered in their attempts to chlorinate the P–P bond in 9 that treatment with PCl₅ or PCl₃ leads to formation of (η³)-P₃Cr(CO)₂Cp, 61, a cyclo-P₃ complex of chromium and the chlorinated byproduct (CpCr(µ-Cl)Cl)₂ (Scheme 3).⁸⁵ This is a potentially useful example of phosphorus ligand reactivity as it demonstrates a method for addition of a phosphorus atom to a P₂ ligand. Furthermore, in this report the authors show that not only can PCl₃ be used to make a P₃ complex, but also that AsCl₃ can be used instead, in which case the obtained product is (η³-P₂As)Cr(CO)₂Cp, 62, the first example of a cyclo-P₂As ligand complexed to a metal center.⁸⁵

Another progression of reactions derived from a bridging P₂ complex has stemmed from the diniobium complex 16. It was recognized that the P₂ unit in 16 could be further reduced by two electrons to afford a mono-anionic terminal phosphide complex. Reduction of 16 with an excess of sodium amalgam produced yellow [Na][P≡Nb(N[CH₂Bu]Ar)₃] (63) in 65% yield (Scheme 4).⁸⁶ This complex can also easily be synthesized without isolation of the intermediate bridging
P₂ complex, making it readily accessible from P₄ in a one-pot synthesis. The phosphorus NMR spectrum of 63 displays a resonance at δ = 1010 ppm that is diagnostic of early-transition-metal terminal phosphide complexes.

The terminal phosphide anion complex 63 has served as an entry to various phosphorus-element bond-forming reactions (Scheme 4). It was shown in 2004 that 63 gives rise to phosphaalkynes upon treatment with acid chlorides in a reaction that proceeds through a meta-stable NbPCO metallacycle. The niobium co-product of this reaction, terminal oxo ONb(N[CH₂ᵗBu]Ar)₃, may be recycled back to the P₄-activating starting material. As such, this reaction progression forms a closed synthetic cycle for the formation of a C=P bond in only a few synthetic steps from P₄. The anionic terminal phosphide complex 63 was also shown to add to Mes*N=PCl to afford a diphosphaazide complex, (η²-Mes*N=P=P)Nb(N[CH₂ᵗBu]Ar)₃ that loses the P₂ unit upon gentle thermolysis, or upon coordination of W(CO)₅. Therefore, this molecule serves as a synthon for diphosphorus or the W(CO)₅ complex of P₂, allowing P₂ to be transferred to a variety of compounds including other terminal phosphide complexes which may themselves be derived from P₄ activation, organic dienes, and low-valent metal centers. In addition, reactions of 63 with main-group electrophiles have led to unusual phosphorus-containing ligands such as diorganophosphanylphosphinidenes and µ₂:η³,η³-EP₂ (E = Ge, Sn, Pb) triangles.

5.2 Reactivity and Transfer Chemistry of the Cyclo-P₃ Functional Group

Functionalizations of cyclo-P₃ complexes were first reported for the series (P₃)M(triphos) (M = Co, Rh, Ir) and required the highly electrophilic reagents [Me₃O][BF₄] or MeOTf to afford the
methylated species.\textsuperscript{91} It was shown by Piro and Cummins in 2008 that the anionic nature of the \textit{cyclo}-P\textsubscript{3} complex [Na][W(CO)\textsubscript{5}P\textsubscript{3}Nb(N[CH\textsubscript{2}tBu]Ar)\textsubscript{3}], derived from P\textsubscript{2}W(CO)\textsubscript{5} trapping by 63, imparts the molecule with greater nucleophilic character, allowing for functionalization using milder reagents to give a variety of products.\textsuperscript{78,92} Though this anionic \textit{cyclo}-P\textsubscript{3} complex was not obtained directly from P\textsubscript{4} activation, its reactivity provided inspiration for the study of the reaction chemistry of the anionic \textit{cyclo}-P\textsubscript{3} molecule 23 which was derived from P\textsubscript{4} activation. Complex 23 was found to be capable of P\textsubscript{3}\textsuperscript{3−} transfer to appropriate E\textsuperscript{3+} sources and this methodology provided the first selective synthesis of the tetraatomic interpnictide AsP\textsubscript{3} by reaction of 23 with 1 equiv of AsCl\textsubscript{3} with loss of NaCl and Cl\textsubscript{2}Nb(ODipp)\textsubscript{3}(THF) (Scheme 5).\textsuperscript{39} The chemistry of AsP\textsubscript{3}, which is synthetically available in two steps from P\textsubscript{4}, is now being studied in detail.\textsuperscript{39,93}
5.3 Functionalization and Transfer Chemistry of Polyphosphorus Ligands (P≥4) Derived from P₄

The chemistry of P₄-derived polyphosphorus ligands (Pₙ, n≥4) in an ETM context has not been explored extensively. The sole example of transformation and transfer of Pₙ ligands (n≥4) from an ETM is confined to the chemistry of 52. Notably, 52 was found to react with ketones (OCR₂) in a metathesis reaction to produce an equivalent of oxo ONb(OC[²Ad]Mes)₃ and phosphaalkene complexes R₂C=PP₇Nb(OC[²Ad]Mes)₃. In cases where the ketone substituents R = aryl, the phosphaalkene complexes obtained via that phospha-Wittig reactivity were unstable with respect to a rearrangement that provided a saturated P₈ cluster containing an internalized R₂C unit (64, Scheme 6). It was further found that the R₂CP₈ ligand could be transferred from the remaining niobium metal center by treatment with an equivalent of pyridine-N-oxide, ONC₅H₅, leading to release of another oxo equivalent, ONb(OC[²Ad]Mes)₃. In the presence of excess 1,3-cyclohexadiene the organic product of Diels-Alder trapping of the liberated diphosphene unit, R₂CP₈(C₆H₈), 65, was formed, isolated, and subjected to structural characterization (Scheme 6).

Scheme 6
6 Concluding Remarks

6.1 Conclusions

The activation of elemental phosphorus by ETM complexes has developed into a rich field rife with impressive structural motifs and transformation methodologies. ETM systems have the ability to promote the formation of and to stabilize a wide range of phosphorus ligands that can themselves act as a foundation for the synthesis of new transition-metal and main-group molecules. Transformation of white phosphorus mediated by early transition metals has opened doors permitting access to the chemistry of intriguing phosphorus-containing molecules including an all-inorganic analogue of titanocene, the diatomic P$_2$ molecule, and the tetra-atomic AsP$_3$ molecule, in addition to a host of monocyclic and polycyclic phosphides that allow for further cementing of the diagonal relationship between the HC functional group on the one hand and a P atom on the other.$^{61}$

ETM systems have a proven ability to reduce the P$_4$ tetrahedron and stabilize reactive P–P bonds sufficiently to allow for further elaboration and manipulation while still maintaining the potential to transfer the newly built structures off of the transition metal foundation. These abilities ensure a prominent place for early transition metals in the future development of new P$_4$ transformation methodologies. With more than 30 years of chemistry documented between P$_4$ and ETM complexes, a library of P-ligands has emerged and general reactivity motifs have been revealed. The three strategies most commonly employed for P$_4$ activation include treatment with a low valent, sterically hindered ETM complex; photolysis or thermolysis in the presence of an ETM carbonyl complex; and \textit{in situ} reduction of an ETM precursor in the presence of P$_4$. Depending on the electronic and steric properties of the ETM complex, P-ligands of different nuclearity can be obtained and we are beginning to understand the possible bonding motifs between phosphorus and ETM centers.

Careful study of the amassed library of information will now allow researchers to begin to predict what type of phosphorus activation products might be obtained from a given reaction. Figure 11 shows the frequency of occurrence of a given P$_n$ ($n = 1 - 8$) ligand derived from P$_4$ activa-
tion by an ETM complex versus \( n \). Not surprisingly, formation of \( P_4 \) ligands appears to be the most common outcome of ETM white phosphorus activation. It can be seen from this plot that phosphorus ligands with even numbers of P-atoms occur more frequently than their odd numbered counterparts. This suggests that phosphorus degradation more often occurs in a symmetric fashion, leading to many isolated \( P_2 \) products. It is noteworthy, however, that nearly all of the \( P_2 \) complexes are bimetallic species, while most of the \( P_1 \) and \( P_3 \) complexes are monometallic in nature. One further observation is that \( P_n \) ligands with \( n \geq 5 \) occur far less frequently than ligands with \( n \leq 4 \). It is likely that these \( P_4 \) aggregation products are the result of kinetic trapping of highly reactive \( P_4 \) degradation products with themselves or with \( P_4 \) and cannot really be rationally predicted or anticipated. The relatively high frequency of \( P_6 \) ligands represents an exception here and would suggest that \( P_2 \) trimerization or \( P_2 \) trapping by \( P_4 \) ligands is favorable. The data set here is reasonably small so it remains difficult to be able to use such information in an explicitly predictive way, but it does shine light on general principles of \( P_4 \) activation that are emerging and helps to motivate researchers to continue to study \( P_4 \) activation to help develop a greater understanding of that process.

Figure 11: Frequency of \( P_n \) ligands formed from \( P_4 \) activation by ETM complexes as a function of \( n \).
6.2 Future Prospects

Despite the resurgence of activity and growth in phosphorus activation and the chemistry promoted by it, there are still few processes capable of converting $\text{P}_4$ into organophosphorus molecules directly without going through $\text{PCl}_3$ as an intermediate, virtually no catalytic methods for the functionalization of $\text{P}_4$ have been documented, and consequently, no industrial scale processes for the direct formation of P–C bonds are in use. Researchers in the field are beginning to develop methods of P–C bond formation from $\text{P}_4$, but these initial investigations have only just begun to scratch the surface of the potential goldmine of new methodologies left to be uncovered. Additionally, there has been little mechanistic work done to support the mass of synthetic research accomplished to date. Mechanistic investigations would greatly enhance our ability to predict the outcomes of and design new transformations in ETM $\text{P}_4$ activation chemistry. The significant recent advances in the field of ETM $\text{P}_4$ activation documented here show the breadth of chemistry that $\text{P}_4$ can undergo and the unrealized goals of phosphorus chemistry support the need for continued work in this area. It is hoped that this review will not only inspire future researchers to new chemical discoveries, but also drive others to employ molecular phosphorus as a synthon in their own research.

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References


(36) di Vaira, M.; Stoppioni, P.; Peruzzini, M. Polyhedron 1987, 6, 351–382.


**Biographies**

Christopher C. Cummins, a.k.a. “Kit”, elucidated C–H bond activation and other chemistry of low-coordinate titanium and zirconium imido complexes while an undergraduate student in the laboratory of Prof. Peter T. Wolczanski at Cornell University. Also while at Cornell, Kit was inspired by the theoretical chemistry teachings of Roald Hoffmann. For his Ph.D. studies, Kit joined the laboratory of Prof. Richard R. Schrock at the Massachusetts Institute of Technology, where he divided his research between synthesizing semiconductor nanoparticles within block-copolymer microdomains and initiating a project on the transition-element coordination chemistry of triamidoamine ligands. Upon beginning his career as an independent investigator and faculty member, also in the MIT Department of Chemistry, Kit launched a program of research aimed at small-molecule activation, inorganic functional group synthesis, and group transfer reactions. Signature discoveries that have issued from this program include complete six-electron reductive cleavage of N\(_2\) by three-coordinate molybdenum(III) complexes, selective cleavage of the nitrous oxide N—N bond, terminal phosphide M≡P triple bond synthesis via P\(_4\) activation, establishment of the terminal carbide functional group, structure and reactivity of a terminal PO complex, creation of a synthon for solution reactivity of the P\(_2\) molecule, and the synthesis and isolation of AsP\(_3\) as a pure substance. Ongoing research projects in Kit’s laboratory are in the areas of group 15 element chemistry as mediated by early-transition metals, uranium-element multiple bonding, carbon dioxide reduction, and ligand architectures for the molecular chemistry of renewable energy. For more information please visit [http://web.mit.edu/ccclab](http://web.mit.edu/ccclab).
Brandi Cossairt is a graduate student in the Cummins research group at MIT. She has been studying the activation of white phosphorus by niobium complexes. Her studies have demonstrated \( P_4 \) reductive coupling by niobium enolate compounds, and subsequent synthesis of phosphorus-rich organic molecules. Moving from enolate to aryloxide supporting ligands, Brandi discovered an efficient \( \text{cyclo-P}_3 \) complex synthesis. The so-obtained anionic niobium \( \text{cyclo-P}_3 \) complex is effective as a \( P_3^{3-} \) transfer agent, leading in turn to the synthesis and isolation of \( \text{AsP}_3 \) as a pure substance. Brandi was an undergraduate at Caltech, where she co-authored papers in both physical and inorganic chemistry. Brandi grew up in Miami, Florida.

Nicholas Piro received his Ph.D. from MIT in June 2009. As a graduate student in the Cummins Group he studied the transformations of \( P_4 \)-derived phosphorus ligands atop a niobium trisanilide platform. His research included the development of a solution phase source of a diatomic \( P_2 \) synthon that he later used in the synthesis of more phosphorus-rich coordination complexes, including
cyclo-P₃ complexes and σ-complexed tetraphosphabenzenes. Prior to arriving at MIT, Nick was an undergraduate at Caltech where he studied the group 10 chemistry of iso-bipyridyl and related ligands under the tutelage of Prof. John Bercaw. Nick is currently a Miller Research Fellow at UC Berkeley.

Figure 14: Nicholas A. Piro