P_4 Activation

DOI: 10.1002/anie.200704305

New Routes for the Functionalization of P_4

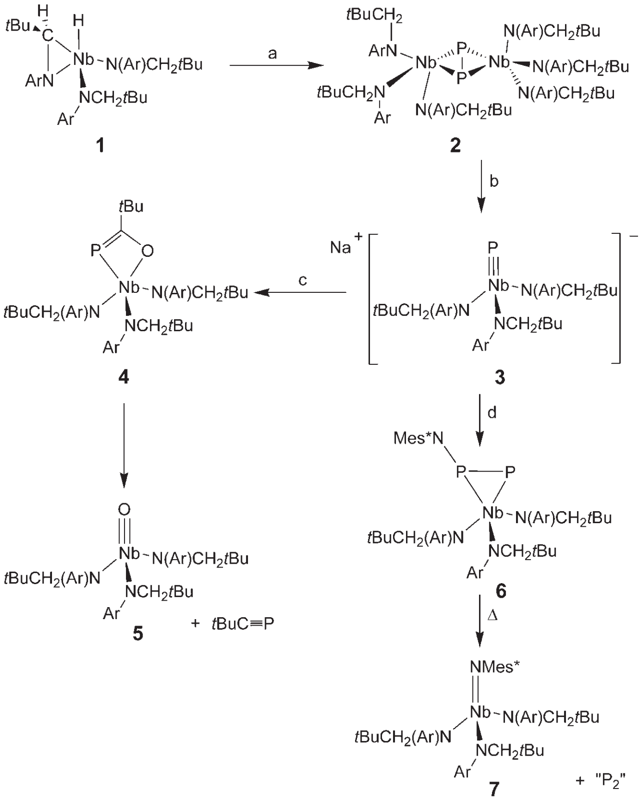
*Jason M. Lynam**

bond activation · carbenes · phosphorus · transition metals

The activation and derivatization of small, readily available molecules represents an important process in laboratory, industrial, and environmental contexts. Many studies have focused on the activation of molecules such as CH_4, CO_2, H_2, and N_2, and often transition-metal reagents have been employed for these processes. One further small molecule that has more recently become a target for controlled activation is white phosphorus, P_4. This species is readily available and provides a key entry point into many aspects of phosphorus chemistry. Indeed, it is a far more attractive target for derivatization than, for example, phosphates, in which strong P–O bonds must be cleaved. Classical methods to activate elemental phosphorus focus either on direct reaction with halogens to give, for example, PX_3 and PX_5 (X = halogen) or hazardous reductions by alkali metals to give salts of the P^{3-} anion which may be quenched with electrophilic reagents. However, the alkali-metal reduction of P_4 has been shown to produce some structurally important compounds such as the $[P_4]^{2-}$ dianion.[1]

It is therefore evident that safer, controlled routes to phosphorus compounds from P_4 would be highly valuable. Unsurprisingly, in the search for suitable catalytic processes, the interaction of transition metals with white phosphorus has been extensively studied, and in this context a remarkable number of different activation pathways have been described.[2] More recently, attention had been focused not only on the coordination and activation of P_4 but on subsequent functionalization. For any such process to be synthetically viable, the initial coordination of P_4 to the metal center must be selective and high-yielding, as must any subsequent steps in the reaction. Furthermore, coordination must either lead to P–P bond cleavage or facilitate novel reactivity. Although no catalytic processes have been reported to date, several metal-promoted stoichiometric transformations of P_4 that meet the above criteria have been described. For example, Peruzzini et al.[2] have demonstrated that P_4 coordinates to a series of half-sandwich compounds to give complexes such as $[Ru(\eta^5\text{-}C_5H_5)(PPh_3)_2(\eta^1\text{-}P_4)]^+$. Importantly, coordination to ruthenium dramatically alters the chemistry of P_4. Hydrolysis of the white phosphorus becomes facile; for example, reaction of $[Ru(\eta^5\text{-}C_5H_5)(PPh_3)_2(\eta^1\text{-}P_4)]^+$ with water results in the formation of $[Ru(\eta^5\text{-}C_5H_5)(PPh_3)_2(PH_3)]^+$. The generation of the pyrophoric PH_3 ligand within the coordination sphere of the metal is remarkable, and, given that P_4 is stored under water for safety purposes, the contrast between the reactivity of free and coordinated phosphorus toward water is striking. In this reaction, however, the fate of three of the four atoms of white phosphorus is undetermined, although evidence points to the formation of H_3PO_2.

A more atom-efficient metal-mediated derivatization of P_4 has been reported by Figueroa and Cummins.[3,4] As illustrated in Scheme 1, reaction of the niobium hydride **1** with 0.25 equivalents of P_4 results in the formation of the dimeric complex **2**, which may then be transformed into the terminal phosphide **3**, itself a versatile synthon. The reaction of **3** with *t*BuCOCl yields the metallacycle **4**, which on



Scheme 1. Activation of P_4 with a niobium hydride complex; Ar = C_6H_3-3,5-Me_2. a) 0.25 P_4; b) Na/Hg; c) *t*BuCOCl, −NaCl; d) Mes*NPCl (Mes* = C_6H_2-2,4,6-*t*Bu_3), −NaCl.

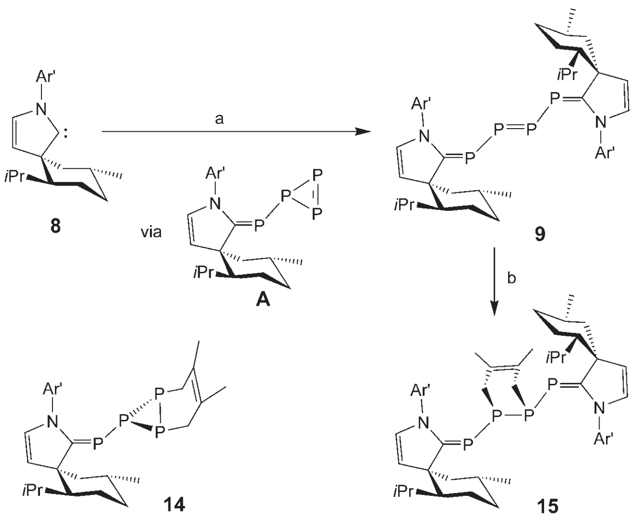
---

[*] Dr. J. M. Lynam
Department of Chemistry
University of York Heslington
York, YO10 5DD (UK)
Fax: (+44) 1904-432-516
E-mail: jml12@york.ac.uk

warming to 70 °C eliminates the phosphaalkyne $t\mathrm{BuC{\equiv}P}$ with concomitant formation of **5**.[5] In some respects, this synthetic method is an exemplar of the new routes to functionalized P_4, as it circumvents the traditional synthesis of $t\mathrm{BuC{\equiv}P}$, which relies on the use of $P(SiMe_3)_3$, prepared from the hazardous reduction of P_4 with Na/K.

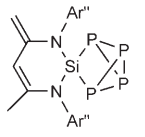
Perhaps the most remarkable reaction observed in this system is centered on the reactivity of **6**.[6] Heating **6** to 65 °C results in the formation of $[Nb\{N(Ar)CH_2t\mathrm{Bu}\}_3(NMes^*)]$ (**7**). The reaction proceeds with formal elimination of P_2, which was captured by the solvent 1,3-cyclohexadiene. Hence, the niobium fragment in this reaction may be considered to be facilitating the transformation of P_4 into P_2, a process that normally only occurs above 1100 K.

Recently, however, Bertrand and co-workers have demonstrated a new way to activate P_4 that does not involve activation by a transition metal; the process also proceeds under very mild conditions.[7] This reaction utilizes the reaction of the stable chiral cyclic alkyl amino carbene (CAAC) **8** with P_4 and results in the formation of **9** in good yield (Scheme 2).

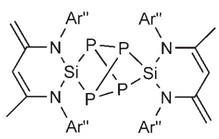


Scheme 2. Activation of P_4 with a carbene; $Ar' = C_6H_3\text{-}2,6\text{-}i\mathrm{Pr}_2$. a) 0.5 P_4; b) 2,3-dimethylbutadiene.

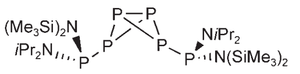
The bond lengths and angles provided by a single-crystal X-ray diffraction study clearly demonstrate that **9** consists of a planar C=P−P=P−P=C framework. It is therefore remarkable that two P=C bonds and one P=P bond are generated in a single reaction under mild conditions. Although multiple bonds to phosphorus are now a well-documented phenomenon,[8] the synthetic routes to these compounds are typically carefully designed and involve either reduction of P−X bonds or elimination reactions. The ability to prepare such structures without the aid of transition metals is unique and contrasts significantly with the reaction of P_4 with heavier carbene analogues that typically result in the formation of sigma-based frameworks. For example, the reaction of P_4 with silylenes has been shown to result in the sequential addition into two P−P bonds. In this case, both the mono- (**10**) and disilylene (**11**) compounds were isolated ($Ar'' = C_6H_3\text{-}2,6\text{-}i\mathrm{Pr}_2$).[9] These compounds provide an interesting and important contrast to the unsaturated double-bond framework of **9**, as it may be envisaged that they will act as masked sources of the $[P_4]^{2-}$ (for **10**) and $[P_4]^{4-}$ (for **11**) ions with retention of the sigma-based framework of white phosphorus. Furthermore, Lappert and co-workers have demonstrated that the activation of P_4 may be achieved with phosphorus-based radicals.[10] In this example, the P−P bond in $(P(Ni\mathrm{Pr}_2)\{N(SiMe_3)_2\})_2$ undergoes homolytic cleavage in solution to give $^\bullet P(Ni\mathrm{Pr}_2)\{N(SiMe_3)_2\}$. Reaction of this equilibrium mixture with P_4 results in the formation of **12**, the location of the $P(Ni\mathrm{Pr}_2)\{N(SiMe_3)_2\}$ fragment providing evidence that the reaction proceeds by a radical pathway.



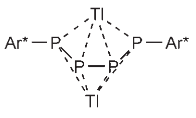
10



11



12



13

A further corollary to the formation of **9** is the report by Power and co-workers[11] of the reaction of P_4 with $(TlAr^*)_2$ ($Ar^* = C_6H_3\text{-}2,6\text{-}(C_6H_3\text{-}2,6\text{-}i\mathrm{Pr}_2)_2$) to give **13**. This product may be viewed as the dithalium salt of the $[Ar^*{-}P{=}P{-}P{=}P{-}Ar^*]^{2-}$ dianion, and the similarity in the construction of a planar P_4 skeleton is apparent. The crucial difference between **9** and **13** is in the order of the unsaturation of the phosphorus backbone; the formation of the C=P and P=P bonds in **9** is presumably facilitated by the availability of the stable carbene, which is formally unsaturated.

The mechanism by which **9** is formed is of obvious interest. On the basis of DFT calculations, Bertrand and co-workers propose that the reaction proceeds by initial nucleophilic attack at phosphorus by the carbene to give a triphosphirene compound **A** (Scheme 2), which then reacts with a second equivalent of carbene to give the reaction product. This hypothesis was given additional credence by the trapping of **A** with 2,3-dimethylbutadiene to give **14**.

One important feature of **9** is that P=P and P=C bonds are reactive and therefore offer the possibility of further functionalization. Indeed, **9** reacts with 2,3-dimethylbutadiene to give **15**. Considering the isolobal P↔CH and diagonal P/C relationships, this reaction may simply be viewed as a classical Diels–Alder reaction. In this light, compound **15**, which contains a complex organophosphorus skeleton, has been prepared in two steps from P_4; the formation of the two new P−C bonds also proceeds with high diastereoselectivity.

Perhaps the most remarkable aspect of this and several other recent reports by Bertrand and co-workers[12] is that carbene **8** is able to perform transformations that are generally considered to be the domain of transition metals. For example, CAACs bind CO to give ketenes, and they may cleave the H−H bond in dihydrogen and the N−H bond in ammonia; the well-known N-heterocyclic carbenes (NHCs) do not perform these reactions.

The difference in reactivity between CAACs and NHCs and the similarity between CAACs and transition metals may be rationalized by a comparison of the electronic structure of the different species involved. The highest occupied molecular orbital (HOMO) is higher in energy and the singlet–triplet gap smaller in CAACs than in NHCs. CAACs may therefore act as both better nucleophiles and better electrophiles. Indeed, the sum of these effects is that CAACs may act as both donor and acceptor towards a single substrate. Therefore a direct analogy between the classical synergic donor–acceptor interactions between a transition metal and a substrate, which represents the basis of the oxidative addition process, may be made. Using the example of dihydrogen, electron density is donated from the H_2 σ orbital to the vacant carbene p orbital with concomitant back-donation from the full carbene HOMO to the H_2 σ* orbital. The result of each of these interactions is to weaken and ultimately cleave the H–H bond. These orbital interactions are depicted in Figure 1 for both a transition metal and a carbene with dihydrogen. Although the topology of the orbitals in CAACs is different to that observed in metal complexes, it is evident that the presence of both donor and acceptor orbitals at the correct energy is crucial to these activation processes. Moreover, a significant problem in the activation of, for example, the N–H bonds in ammonia and the P–P bonds in P_4 by transition metals is that the formation of simple coordination compounds may compete with the desired bond cleavage and lead to unproductive pathways; the high nucleophilicity of CAACs circumvents this problem. As the electronic structure of carbenes may be subtly tuned by the nature of the substituents, the reactivity of these species may be modulated to perhaps generate organocatalytic processes.

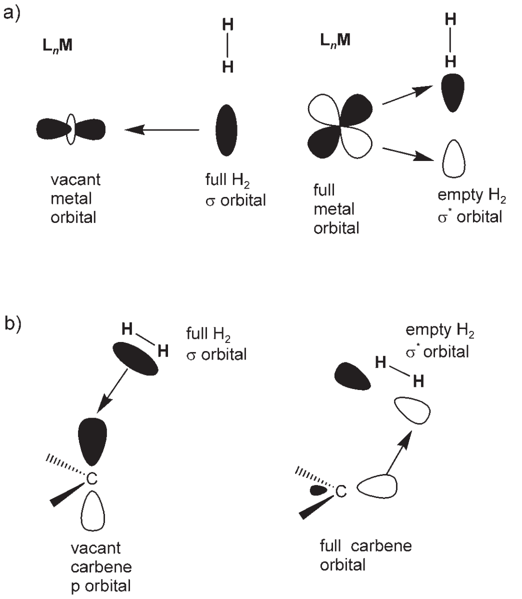


Figure 1. Orbital interactions between a transition metal and dihydrogen (a) and between a carbene and dihydrogen (b).

The challenge of converting all four phosphorus atoms of P_4 into a single product (atom-efficient in phosphorus) in a catalytic fashion is still an unachieved goal. However, the reactions described above, the facile formation of PH_3, the transformations mediated by niobium to give effectively a source of P_2, and the formation of **9**, represent significant advances in this field. Given the widespread application of organophosphorus compounds in transition-metal catalysis, there is a significant demand for novel, high-yield, and selective methodologies. Harnessing the chemistry of P_4 represents an important strategy in this search. Furthermore, the design and synthesis of stable but highly reactive enantiomerically pure carbenes, such as **8**, presents a significant opportunity for the activation of a range of small molecules and facile preparation of chiral organophosphorus compounds from P_4.

---

[1] F. Kraus, J. C. Aschenbrenner, N. Korber, *Angew. Chem.* **2003**, *115*, 4162; *Angew. Chem. Int. Ed.* **2003**, *42*, 4030.

[2] M. Peruzzini, L. Gonsalvi, A. Romerosa, *Chem. Soc. Rev.* **2005**, *34*, 1038, and references therein.

[3] J. S. Figueroa, C. C. Cummins, *Dalton Trans.* **2006**, 2161.

[4] C. C. Cummins, *Angew. Chem.* **2006**, *118*, 876; *Angew. Chem. Int. Ed.* **2006**, *45*, 862.

[5] J. S. Figueroa, C. C. Cummins, *J. Am. Chem. Soc.* **2004**, *126*, 13916.

[6] N. A. Piro, J. S. Figueroa, J. T. McKellar, C. C. Cummins, *Science* **2006**, *313*, 1276.

[7] J. D. Masuda, W. W. Schoeller, B. Donnadieu, G. Bertrand, *Angew. Chem.* **2007**, *119*, 7182; *Angew. Chem. Int. Ed.* **2007**, *46*, 7052.

[8] K. B. Dillon, F. Mathey , J. F. Nixon *Phosphorus, The Carbon Copy*, Wiley, Chichester, **1998**.

[9] Y. Xiong, S. Yao, M. Brym, M. Driess, *Angew. Chem.* **2007**, *119*, 4595; *Angew. Chem. Int. Ed.* **2007**, *46*, 4511.

[10] J.-P. Bezombes, P. B. Hitchcock, M. F. Lappert, J. E. Nycz, *Dalton Trans.* **2004**, 499.

[11] A. R. Fox, R. J. Wright, E. Rivard, P. P. Power, *Angew. Chem.* **2005**, *117*, 7907; *Angew. Chem. Int. Ed.* **2005**, *44*, 7729.

[12] a) V. Lavallo, Y. Canac, B. Donnadieu, W. W. Schoeller, G. Bertrand, *Angew. Chem.* **2006**, *118*, 3568–3571; *Angew. Chem. Int. Ed.* **2006**, *45*, 3488–3491; b) G. D. Frey, V. Lavallo, B. Donnadieu, W. W. Schoeller, G. Bertrand, *Science* **2007**, *316*, 439.