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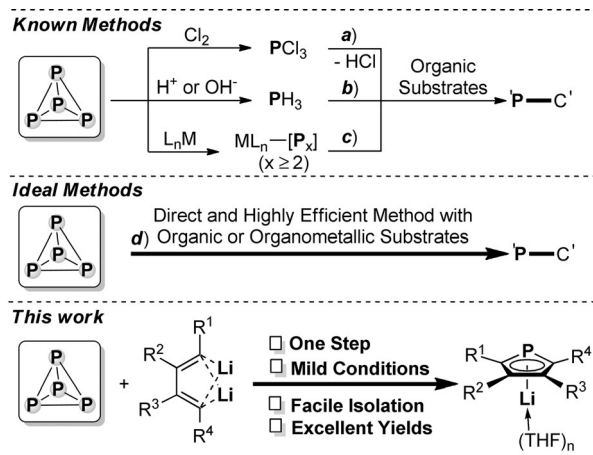
Direct Synthesis of Phospholyl Lithium from White Phosphorus

Ling Xu, Yue Chi, Shanshan Du, Wen-Xiong Zhang,* and Zhenfeng Xi

Dedicated to Professor Li-Cheng Song on the occasion of his 80th birthday

Abstract: The selective construction of P–C bonds directly from P₄ and nucleophiles is an ideal and step-economical approach to utilizing elemental P₄ for the straightforward synthesis of organophosphorus compounds. In this work, a highly efficient one-pot reaction between P₄ and 1,4-dilithio-1,3-butadienes was realized, which quantitatively affords phospholyl lithium derivatives. DFT calculations indicate that the mechanism is significantly different from that of the well-known stepwise cleavage of P–P bond in P₄ activation. Instead, a cooperative nucleophilic attack of two C_{sp²}Li bonds on P₄, leading to simultaneous cleavage of two P–P bonds, is favorable. This mechanistic information offers a new view on the mechanism of P₄ activation, as well as a reasonable explanation for the excellent yields and selectivity. This method could prove to be a useful route to P₄ activation and the subsequent production of organophosphorus compounds.

Organophosphorus compounds have been widely used as agrochemicals, detergents, and flame retardants.^[1] They can also serve as versatile ligands in coordination chemistry, organometallic chemistry, and metal-mediated organic synthesis. Generally, the vast majority of phosphorus atoms in organophosphorus compounds are derived from white phosphorus (P₄).^[2] However, multistep and environmentally toxic processes are usually involved to make organophosphorus compounds from elemental P₄, either via phosphorus halides (such as PCl₃, PCl₅, Scheme 1a) or via the extremely toxic phosphine (PH₃) gas (Scheme 1b). Although metal-mediated P₄ activation to construct P–C bonds is a promising strategy because it releases far less pollution (Scheme 1c), it generally suffers from very low reaction selectivity between the formed L_nM–[P_x] (x ≥ 2)^[3,4] and organic reagents.^[5] To make this promising approach practical, the following two problems should be overcome: 1) the activated P atoms in the [P_x] moiety may act as nucleophilic sites, which leads to poor regioselectivity with organic substrates, and 2) the reactivity



Scheme 1. Construction of P–C bonds.

difference among the P–P bonds in the [P_x] moiety is small. From the view point of sustainability and green chemistry, the direct and highly efficient construction of P–C bonds from P₄ and organic or organometallic substrates is an ideal process (Scheme 1d).

Generally, the reaction between simple organomono-lithium reagents and P₄ affords a complicated mixture, whatever the molar ratio of organolithium reagents to P₄ applied and regardless of reaction conditions, although the utilization of bulky substituent can lead to phosphorus rich compounds.^[6,7] We envision that the reaction of organo-dilithium reagents, for example, 1,4-dilithio-1,3-butadienes, which have a dilithium bridge,^[8] with P₄ might yield interesting compounds because cooperative nucleophilic attack of two C_{sp²}–Li bonds on P₄ could selectively trap one phosphorus atom. Herein, we report a straightforward synthesis of phospholyl lithium compounds from P₄ and 1,4-dilithio-1,3-butadienes. Phospholyl ligands have played a vital role in coordination chemistry and organometallic chemistry because they can stabilize various metals in common oxidation states or low oxidation states.^[9,10] This preparative method for phospholyl lithiums has the following advantages: step-economy, mild conditions, facile isolation, and excellent yields based on the dilithium reagents.

Initially, we attempted a 1:1 molar ratio reaction between dilithium reagent **1a** and P₄ in THF. When a THF solution of **1a** was added to a THF solution of P₄, a large amount of yellow-brown solid formed immediately to give a suspension. The suspension was stirred overnight and the solution turned clear with a dark brown solid on the wall of the flask. The

[*] Dr. L. Xu, Y. Chi, S. Du, Prof. Dr. W.-X. Zhang, Prof. Dr. Z. Xi
Beijing National Laboratory for Molecular Sciences (BNLMS)
Key Laboratory of Bioorganic Chemistry and Molecular Engineering
of Ministry of Education, College of Chemistry, Peking University
Beijing 100871 (China)
E-mail: wx_zhang@pku.edu.cn
Prof. Dr. W.-X. Zhang
State Key Laboratory of Elemento-Organic Chemistry
Nankai University, Tianjin 300071 (P.R. China)

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solution was then decanted to another flask. After removing the solvent under reduced pressure, product **2a** could be obtained quantitatively. Single crystals of **2a** were obtained from a THF/hexane solution of **2a**. X-ray analysis of **2a** revealed that it is a phospholyl lithium in which the lithium atom is coordinated by a phospholyl in η^5 mode and two THF molecules in κ^1 mode (Figure 1).

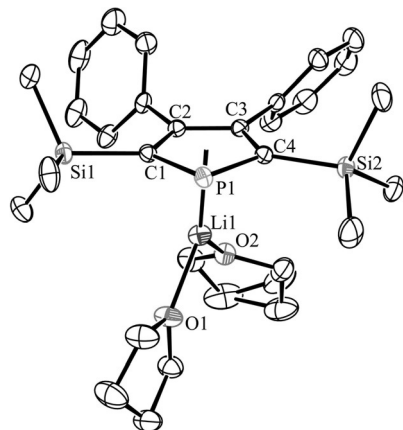
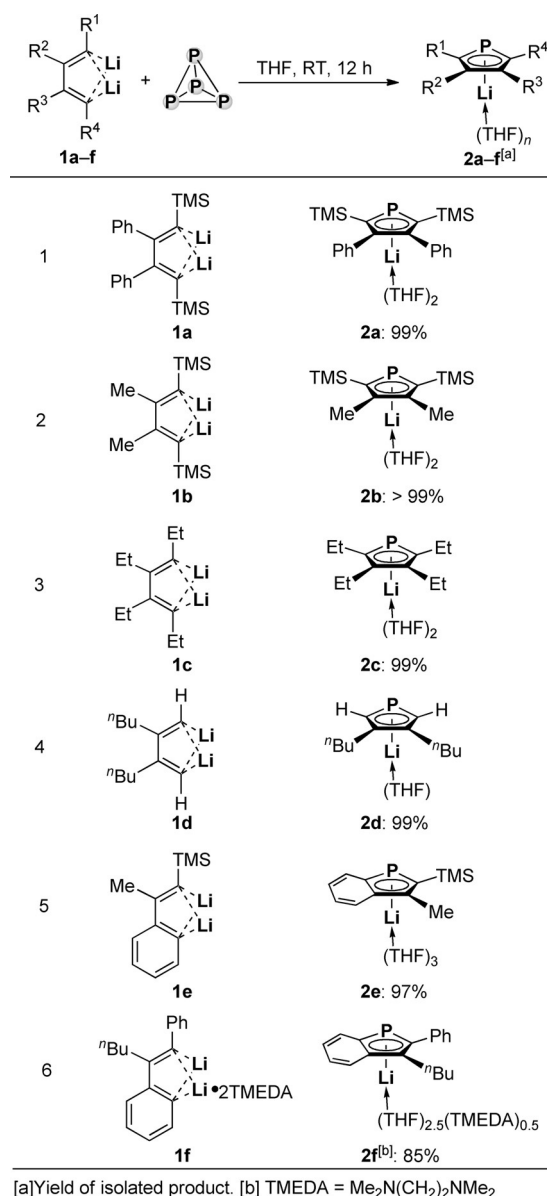


Figure 1. Molecular structure of **2a**. All hydrogen atoms are omitted for clarity, and ellipsoids are shown at 30% probability. One carbon of THF is disordered.

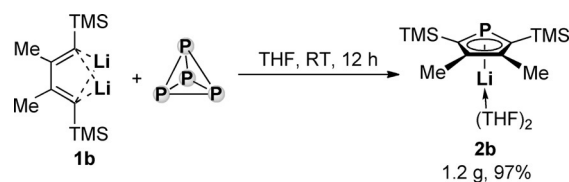
Dilithium reagents bearing different substituents^[8d] can be applied in the presented reaction (Scheme 2). When 1,4-bis(trimethylsilyl)-2,3-dimethyl-1,4-dilithiobutadiene (**1b**) was applied as the starting material, the corresponding **2b** could be obtained quantitatively. In addition to α -trimethylsilyl-substituted dilithium reagents, the reaction of tetraalkyl-substituted dilithium reagents, for example, 1,2,3,4-tetraethyl-1,4-dilithiobutadiene (**1c**), with P_4 led to quantitative production of the corresponding product **2c**. Interestingly, 2,3-dibutyl-1,4-dilithiobutadiene (**1d**) was also applied in this reaction and quantitatively afforded the disubstituted phospholyl lithium **2d**. Furthermore, the styrene-type dilithium reagent **1e** was reacted with P_4 to give the phosphindolyl lithium **2e**. Another styrene-type dilithium reagent, **1f**, which can be easily prepared from n BuLi and diphenylacetylene in TMEDA,^[8e] also gave the corresponding product **2f** in 85% yield under the presented conditions.

This reaction could also be carried out on a preparative scale, thereby demonstrating its practical usefulness (Scheme 3).

Despite the fact that phospholyl lithiums can be obtained through several known routes,^[9,10e,11] practical routes to obtain phospholyl lithiums require at least three steps from the starting P_4 : 1) the chlorination of P_4 to afford PCl_3 ; 2) the synthesis of phospholes; and 3) cleavage of the P–C/P–Cl bond of phospholes. These multistep synthetic routes to phospholyl lithiums are both time-consuming and cost-intensive owing to the numerous reactions and corresponding isolations. However, the development of new synthetic methods to phospholyl lithium has been very limited over the past century, with the exception of the recent work of



Scheme 2. One-step synthesis of phospholyl lithiums.



Scheme 3. Synthesis of **2b** on a preparative scale.

Duan and co-workers.^[12] The present method enables the practical, highly efficient, and convenient preparation of differently substituted phospholyl lithiums.

The interesting and novel results of the work reported herein prompted us to ponder why the reaction of 1,4-dilithio-1,3-butadienes with P_4 can yield cleanly phospholyl lithiums. To gain some mechanistic information, different ratios of 1,4-dilithio-1,3-butadienes to P_4 were tested. When the number of

equivalents of P_4 was increased to 1.5, similar results to those with 1.0 equiv can be obtained. However, when the number of equivalents of P_4 was decreased to 0.5 or 0.25, only a mixture could be obtained. These results clearly show that the reaction requires at least 1.0 equiv of P_4 . However, only one phosphorus atom is incorporated into a phospholyl lithium. Thus, three phosphorus atoms may be released as a structurally unknown insoluble polyphosphide $[LiP_3]_n$.

Based on this information, we proposed a mechanism involving the butterfly-like P_4 intermediate **IM1**, which is widely observed in some processes involving aryl lithium reagents (see Scheme S1 in the Supporting Information).^[3d,7a] To gain more insight into this reaction, DFT calculations were carried out with Gaussian 09. All of the intermediates and transition states were fully optimized at the B3LYP level using the 6-31 + G(d) basis set in the gas phase. However, the DFT calculations do not support the existence of **IM1'** in the present process (Scheme 4 and Figure 2). From the calculation result, the first step is the coordination of P_4 to one lithium of 1,4-dithio-1,3-butadiene, affording the intermediate **IM1**. The transformation of **IM1** into **IM2** then takes place in a single step, in which two P–P bonds are cleaved simultaneously with the concomitant formation of two new P–Li bonds and a P–C bond. The barrier to the transition state **TS1** is 24.7 kcal mol^{−1} in the gas phase, and only

9.6 kcal mol^{−1} in THF. Thus, the process from **IM1** to **IM2** can be viewed as the cooperative insertion of one P atom into one head of the C_2 – Li_2 bridge. This step is in strong contrast to the well-known mechanism of stepwise P–P bond cleavage in the reaction of P_4 with nucleophilic reagents. Finally, C–P bond coupling via the cyclization transition state **TS2** affords **2c** with the release of $[LiP_3]_n$.

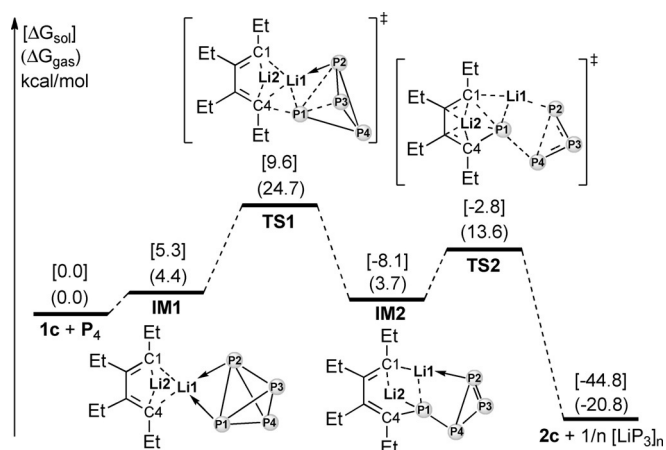
In summary, we have developed a method to access phospholyl lithiums directly from P_4 and 1,4-dithio-1,3-butadienes through a cooperative nucleophilic attack of two C_{sp^2} –Li bonds on P_4 . A broad range of di- or tetrasubstituted phospholyl lithium reagents bearing different alkyl, aryl, or silyl groups can be prepared conveniently and efficiently. In addition, a novel cooperative insertion mechanism in the reaction of P_4 with 1,4-dithio-1,3-dienes is proposed and was confirmed by DFT calculations. This understanding of the process will open new opportunities for the design of straightforward syntheses of organophosphorus compounds from P_4 .

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Keywords: C–P coupling · P_4 functionalization · phospholyl lithium · phosphorus · synthetic methods

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Scheme 4. DFT-calculated potential-energy surfaces of the reaction between **1c** and P_4 .

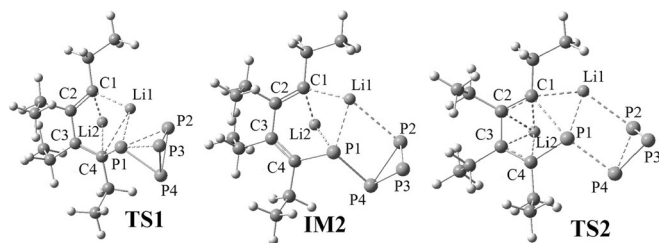


Figure 2. Optimized structures of **TS1**, **IM2**, and **TS2**. Selected bond lengths (Å) of **TS1**: C1–Li1 2.056, C4–Li1 2.545, P1–Li1 2.242, C4–P1 2.201, P1–P2 2.297, P1–P3 2.643. Selected bond lengths (Å) of **IM2**: C1–Li1 2.094, C1–Li2 2.021, P1–Li1 2.370, P1–Li2 2.561, P2–Li1 2.861. Selected bond lengths (Å) of **TS2**: C1–Li1 2.172, C1–P1 2.359, P1–Li1 2.374, P2–Li1 2.588, P1–P4 2.454, P2–P4 2.276.

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