COMMUNICATION

Robert Wolf et al.
Di-tert-butylphosphatetrahedrane as a building block for phosphaalkenes and phosphirenes
Di-tert-butylidiphosphatetrahedrane as a building block for phosphaalkenes and phosphirenes†

Gabriele Hierlmeier, Maria K. Uttendorfer and Robert Wolf‡*

The remarkable ‘mixed’ diphosphatetrahedrane (tBuCP)2 (1) – which is both the elusive dimeric form of the phosphaalkyne tBuCP and an isolobal analogue of the important industrial feedstock P4 – was recently isolated for the first time; however, its chemistry remains unexplored. Herein we report that treatment of 1 with various N-heterocyclic carbenes readily yields unusual, unsaturated organophosphorus motifs. These results demonstrate the significant potential of 1 as a building block for the synthesis of previously unknown organophosphorus compounds.

Organophosphorus compounds (OPCs) are of high industrial and academic importance due to their widespread applications, e.g. as specialty chemicals, pharmaceuticals or ligands in homogeneous catalysis.1,2 The development of suitable synthetic building blocks is a high priority for broadening the range of available OPCs. Traditional reagents available are chlorinated P compounds (e.g. PCl3, PCl5, and OPCl3), monophosphane (PH3),3 and, in very selected cases, phosphoric acid and phosphates.4 In addition, low-coordinate phosphorus compounds such as phosphaalkynes R–C≡P (R = alkyl, aryl; see Fig. 1a)5–8 and, more recently, phosphacyanate salts have also received attention as versatile building blocks.9–11

Nearly all organophosphorus building blocks are ultimately derived from white phosphorus (P4) as the single common precursor. Therefore, fundamental reactivity studies on P4 are of high importance.12 As early as 1963, Rauhut and Semsel reported the synthesis of (cyclo)polyphosphides and primary phosphines (e.g. phenylphosphine) after hydrolytic work-up by reacting P4 with organolithium and –magnesium compounds.13,14 This approach has gained renewed interest recently through the work of Lammertsma and Xu.15,16 Bertrand and co-workers studied the reactivity of stable carbenes towards P4 (see Fig. 1b).17–20 Both acyclic and N-heterocyclic carbenes (NHCs) were used, and the nature of the obtained products strongly depends on the steric and electronic properties of the carbene. Using a bulky menthyl- and diisopropylphenyl-substituted cyclic alkyl aminocarbenes (MentCAAC) or 1,3-bis(2,6-diisopropylphenyl)imidazolin-2-ylidine (SIPr), the triphosphirene A was generated.17,18 This species was trapped and characterised as a cycloaddition product with 2,3-dimethylbutadiene. Upon

Fig. 1. (a) Examples of common building blocks used for the synthesis of organophosphorus compounds. X = H, Cl. (b) Reactivity of carbenes toward tBuCP, P4 and (tBuCP)2.17,18,21,22 (c) Reactivity of 1 toward carbenes.
addition of another equivalent of carbene, A converts to the tetraphosphene B. For other NHCs, an aggregation of P₂ to larger polyphosphorus clusters and the degradation even down to monophosphorus fragments was observed.¹⁹,²⁰

Stephan and co-workers synthesised compounds similar to A and B by reacting various NHCs with tert-butylnaphthaldehyde (see Fig. 1).¹¹,²² The phosphaalkene structure C is stable and can be isolated when a diamidocarbene is used.²³ Using a specific cyclic alkylation carbene (CAAC), the dimerisation of the phosphaalkene is observed, resulting in the formation of a diphosphene D.²²

We recently discovered di-tert-butyldiphosphatetrahedrane (tBuCP)₂ (1), which is a rare example of a neutral tetrahedrane comprising two distinct p-block elements and the long-sought-after dimer of tBuCP.²³⁻²⁵ The ready accessibility of 1 via a simple nickel-catalysed process, and its isolobal relationship with Pₓ, prompted us to study its reaction chemistry. For our initial investigations, we chose carbenes to examine whether 1 behaves more like the isolobal Pₓ molecule or the parent monomer tBuCP.

In order to assess the impact of the steric and electronic properties of the NHC, a range of known NHCs were reacted with 1. With 1,3-di-isopropyl-4,5-dimethylimidazolin-2-ylidene ([iPr]ImMes) and methyl-substituted menthyl-substituted MentCAAC, 3₁P{¹H} NMR spectroscopic monitoring only showed the clean formation of the ladderane (tBuCP)₄ (identified by a singlet at −23.0 ppm).²⁶ (tBuCP)₄ is the formal dimer of 1 and we identified this phosphaalkyl tetramer as the decomposition product of 1.²³ However, the reaction of 1 with TMC (2,3,4,5-tetramethylimidazolin-2-ylidene) proceeds differently, affording a deep orange precipitate after 5 minutes when 1 is added to a solution of TMC in benzene. When dissolved in THF-d₈, this solid gives rise to a singlet at −28.4 ppm in the 3₁P{¹H} NMR spectrum. Dissolution of the precipitate in THF, filtration and subsequent recrystallisation from THF yielded crystals suitable for single crystal X-ray crystallography, which revealed the molecular structure of [(TMC)PC(tBu)], (2, Fig. 2b).

Compound 2 can be described as a vinyl-bridged bis(phosphaalkene) formed by P–P bond cleavage of the (tBuCP)₂ tetrahedron.²⁷ Related reactions of tBuCP and NHCs reported by Stephan and co-workers afford diphosphenes (e.g. D, Fig. 1b). The formation of 2 from 1 and TMC thus highlights the distinct reactivity of 1 compared to tBuCP.²²

The crystallographic analysis of 2 suggests the presence of a C₁–C₂ double bond (1.366(2) Å) in an E configuration. The P–C bonds of the TMC units (P₁–C₁ 1.8637(16) Å and P₂–C₂ 1.8630(15) Å) are elongated compared to common C=P double bonds,²⁸ while the P–C bond lengths of the vinyl group (P₁–C₁ 1.8637(16) Å and P₂–C₂ 1.8630(15) Å) are in the range commonly observed for P–C single bonds.²⁹,³⁰ The P₁–C₃ and P₂–C₄ distances are similar to the values observed for (IMes)PPh (1.763(6) Å) and (TMC)PPh (1.794(3) Å).³¹,³² Due to the presence of two amino substituents at carbon, such “isversely polarised phosphaalkenes” show only a partial double bond character and an inverse polarity of the P=C bond compared to more common hydrocarbyl-substituted phosphaalkenes.³³ Notably, the P=C and C=C bonds in 2 are not conjugated with plane to plane twist angles of 51° (C₁–P₁–C₂ vs. P₁–C₁–C₂) and 53° (C₂–P₂–C₄ vs. C₂–C₁–P₁–C₄).

The molecular structure of 2 was well-reproduced by DFT calculations on the BP86-D3BJ/def2-TZVP level. The presence of an inverse electron density distribution (P²⁻ vs. C²⁺) on the phosphaalkene P=C–π-bonds of 2 is supported by an analysis of the relevant intrinsic bond orbitals (IBO analysis, Fig. 3 top).³³ Notably, the P–C σ-bond also features a slightly distorted electron density distribution, which is polarised to carbon in this case. In addition, low Mayer bond orders for these P–C bonds (1.40 for each bond) indicate a significant contribution of the resonance structure 2-II as expected for inversely polarised phosphaalkenes (Fig. 3 bottom).

Bis(phosphaalkene) 2 was isolated in good yield of 69% as a pure, bright orange solid. The 3₁P{¹H} NMR spectrum of 2 in THF-d₈ exhibits a singlet resonance at −28.4 ppm, which is consistent with chemical shifts reported for (IMes)PPh (−23.0 ppm) and (TMC)PPh (−53.5 ppm).³¹,³² The ¹H NMR spectrum shows one broad resonance assigned to the tBu group and two broad signals for the Me substituents on the tBu backbone. These signals are further split into two sets of signals.

![Fig. 2](https://example.com/fig2.jpg)  
**Fig. 2** (a) Reaction of (tBuCP)₂ with TMC; (b) molecular structure of 2 in the solid state. Thermal ellipsoids are set at 50% probability level. Hydrogen atoms are omitted for clarity. Selected bond lengths [Å] and angles [°]: C₁–C₂ 1.366(2), P₁–C₁ 1.8637(16), P₂–C₂ 1.8630(15), P₁–C₃ 1.7673(17), P₂–C₄ 1.7660(16), N₁–C₃ 1.376(2), N₂–C₃ 1.368(2), N₃–C₄ 1.371(2), N₄–C₄ 1.371(2), C₃–P₁–C₁ 108.69(8), C₄–P₂–C₂ 108.18(7), C₂–C₁–P₁ 120.54(13), C₁–C₂–P₂ 120.37(12).

![Fig. 3](https://example.com/fig3.jpg)  
**Fig. 3** Intrinsic bond orbital of 2 showing the inversely polarised P=C π- and σ-bonds (top) and resonance structures of 2 (bottom).
upon cooling (see ESI,† for details). This fluxional behaviour is presumably caused by slow rotation around the P–C bonds at low temperature. In agreement with the $^1$H NMR data, $^{13}$C{$_1^1$H} NMR data recorded at ambient temperature show only one set of resonances for the $t$Bu groups and one set of resonances for the TMC unit. The UV/Vis absorption spectrum of 1 in THF reveals three bands at 270, 340 and 450 nm, accounting for its orange colour. TD-DFT calculations at the wB97X-D3 def2-SVP level of theory show that the absorption band in the visible part of the spectrum (450 nm) is caused by a HOMO–LUMO transition (n$_{p}$ → $\pi^*$C–C; see the ESI,† for a density difference plot).

An initial reactivity study demonstrates the high lability of the TMC moieties of 2. Reactions with different metal complexes ([AuCl(tht)] [tht = tetrahydrothiophene], [p-cymene]RuCl$_2$)$_2$, [[cod]RhCl$_2$] [cod = 1,5-cyclooctadiene], Ag[Al{OC(CF$_3$)$_3$})$_4$]) and het-thylstannylphosphine with a chlorophosphirene. The UV/Vis absorption spectrum of 1 of resonances for the

The formation of 3a–c from 1 is in stark contrast to analogous reactions of NHCs [1,3-bis(2,4,6-trimethylphenyl)-imidazolidin-2-ylidene] (SIMes), IMes, and IPr with $t$BuCP. In these reactions, the formation of a 1H-phosphirene was observed for Me$_2$DAC, a triphosphole for IMes and a carbene-stabilised ($t$BuCP)$_4$ framework for IPr. It should also be noted that three-membered heterocycles related to 3a–c are formed in reactions of carbenes with other tetrahedrane. The phosphirene A [Fig. 1] is obtained from one equivalent of a CAAC or SiPR and P$_4$, a related cyclopentene is formed by reaction of tetra-torr-butyltetrahedrane ($t$BuC)$_4$ and tetracyanoethylene.

Compounds 3a–c were isolated as yellow solids in 29%–56% yield after removal of the side product ($t$BuC)$_4$ by sublimation and re-crystallisation. $^1$H and $^{13}$C{$_1^1$H} NMR spectra of 3a and 3b dissolved in CD$_2$Cl$_2$ showed the presence of one set of signals for the carbene unit, while the spectra of 3c show two sets of signals, indicating a hindered rotation around the P–C bond in solution at ambient temperature. For each compound, the $^{31}$P{$_1^1$H} NMR spectra show two signals of an AX spin system with chemical shifts of −172.3/−138.9 (3a), −170.0/−47.2 (3b) and −162.9/138.9 (3c, see the ESI†). The doublet observed at high field is assigned to the phosphirene moiety. The observed $^3$J$_{PP}$ coupling constants ($^3$J$_{PP}$ = 296 Hz for 3a, $^3$J$_{PP}$ = 299 Hz for 3b, $^3$J$_{PP}$ = 312 Hz for 3c) and the $^3$J$_{CP}$ coupling constants of the phosphirene P-atom to the carbon ring atoms (50–52 Hz) are

Fig. 4 (a) Reaction of ($t$BuC)$_2$ with aryl-substituted carbenes IMes, IPr and Me$_2$DAC, (b) molecular structures of 3a and 3c in the solid state. Thermal ellipsoids are set at 50% probability level. Hydrogen atoms and positional disorder (in $3c$) are omitted for clarity. Selected bond lengths [Å] and angles [°] for 3a: P1–P2 2.2200(4), P2–C1 1.8502(13), P2–C2 1.8479(13), C1–C2 1.2960(19).
consistent with a covalent P–P single bond. UV/Vis absorption spectra of 3a–c show an intense absorption band at 360 nm tailing into the visible region. This accounts for the bright yellow colour of these solids. DFT calculations on a truncated model compound ([Ph]PP(CtBu)2 ([Ph = 1,3-diphenylimidazol-2-ylidene]) show that the electronic transition corresponding to this wavelength is attributed to the HOMO–LUMO transition from the p-orbital of the phosphorus atom connected to the imidazoliumyl substituent to an empty p-orbital of the former carbene C atom (see ESI† for density difference plot). It seems plausible, that 1H-phosphirenes are intermediates in the formation of bisphosphaalkenes such as 2. However, 3b does not react with TMC to afford a bis(phosphaalkene); instead, a carbene C atom (see ESI, imidazoliumyl substituent to an empty p-orbital of the former phosphorus atom) is formed instead. From the NMR spectrum, reaction behaviour is likely attributed to the different sterics of the NHCs used. Importantly, the reactivity of 1 is clearly distinguished from its monomer tBuCP and resembles P1, and the results suggest that 1 has significant potential for the preparation of hitherto unknown organophosphorus compounds. Further reactivity studies of 1 are in hand.

Financial support by the Fonds der Chemischen Industrie (Keküle Fellowship for G. H.) and the European Research Council (CoG 772299) is gratefully acknowledged. We thank Peter Coburger for valuable advice on DFT calculations and Sebastian Bestgen and Daniel Scott for helpful comments on the manuscript.

Conflicts of interest
There are no conflicts to declare.

Notes and references
1 D. E. C. Corbridge, Phosphorus, Chemistry, Biochemistry and Technology, Elvseier, 2000.
2 W. Schipper, Eur. J. Inorg. Chem., 2014, 1567.
3 M. Bispinghoff and H. Grützmacher, Chimia, 2016, 70, 279.
4 M. B. Geeson and C. C. Cummins, Science, 2018, 359, 1383.
5 M. Regitz, Chem. Rev., 1990, 90, 191.
6 A. Chirila, R. Wolf, J. C. Sloatweg and K. Lammertsma, Coord. Chem. Rev., 2014, 270–271, 57.
7 W. Rösch and M. Regitz, Angew. Chem., Int. Ed. Engl., 1984, 23, 900.
8 W. Rösch and M. Regitz, Synthesis, 1987, 689.
9 A. R. Jupp and J. M. Goicoechea, Angew. Chem., Int. Ed., 2013, 52, 10064.
10 D. Heiß, Z. Benkő and H. Grützmacher, Dalton Trans., 2014, 43, 831.
11 X. Chen, S. Alidori, F. F. Puschmann, G. Santiso-Quinones, Z. Benkő, Z. Li, G. Becker, H.-F. Grützmacher and H. Grützmacher, Angew. Chem., Int. Ed., 2014, 53, 1641.
12 J. E. Borger, A. W. Ehlers, J. C. Sloatweg and K. Lammertsma, Chem. – Eur. J., 2017, 23, 11738.
13 M. M. Rauhut and A. M. Sensel, J. Org. Chem., 1963, 28, 471.
14 M. M. Rauhut and A. M. Sensel, J. Org. Chem., 1963, 28, 473.
15 J. E. Borger, M. S. Bakker, A. W. Ehlers, M. Lutz, J. C. Sloatweg and K. Lammertsma, Chem. Commun., 2016, 52, 3284.
16 L. Xu, Y. Chi, S. Du, W.-X. Zhang and Z. Xi, Angew. Chem., Int. Ed., 2016, 55, 9187.
17 J. D. Masuda, W. W. Schoeller, B. Donnadieu and G. Bertrand, Angew. Chem., Int. Ed., 2007, 46, 7052.
18 J. D. Masuda, W. W. Schoeller, B. Donnadieu and G. Bertrand, J. Am. Chem. Soc., 2007, 129, 14180.
19 G. Back, G. Kuchenbeiser, B. Donnadieu and G. Bertrand, Angew. Chem., Int. Ed., 2009, 48, 5530.
20 C. D. Martin, C. M. Weinstein, C. E. Moore, A. L. Rheingold and G. Bertrand, Chem. Commun., 2013, 49, 4486.
21 L. L. Liu, J. Zhou, L. L. Cao, R. Andrews, R. L. Falconer, C. A. Russell and D. W. Stephan, J. Am. Chem. Soc., 2018, 140, 147.
22 L. L. Liu, L. L. Cao, J. Zhou and D. W. Stephan, Angew. Chem., Int. Ed., 2019, 58, 273.
23 G. Hierlemeier, P. Coburger, M. Bodensteiner and R. Wolf, Angew. Chem., Int. Ed., 2019, 58, 16918.
24 P(CtBu): M.-L. Y. Riu, R. L. Jones, W. J. Transue, P. Müller and C. C. Cummins, Sci. Adv., 2020, 6, eaaz3168.
25 (AsP3): B. M. Cossairt, M.-C. Diawara and C. C. Cummins, J. Org. Chem., 2009, 745, 602.
26 B. Geissler, S. Barth, U. Bergsträsser, M. Slany, J. Durkin, P. B. Hitchcock, M. Hofmann, P. Binger, J. F. Nixon, P. von Raguse Schleyer and M. Regitz, Angew. Chem., Int. Ed. Engl., 1995, 34, 484.
27 P. L. Floch, Coord. Chem. Rev., 2006, 250, 627.
28 P. Pykkö, J. Phys. Chem. A, 2015, 119, 3236.
29 B. Cordero, V. Gómez, A. E. Platero-Prats, M. Revés, J. Chevrefevia, E. Cremades, F. Barragán and S. Álvarez, Dalton Trans., 2008, 2832.
30 P. Pykkö and M. Atsumi, Chem. – Eur. J., 2009, 15, 186.
31 A. J. Arduengo III, J. C. Calabrese, A. H. Cowley, H. V. Rasika Dias, J. R. Goerlich, W. J. Marshall and B. Riegel, Inorg. Chem., 1997, 36, 2151.
32 A. J. Arduengo III, H. V. Rasika Dias and J. C. Calabrese, Chem. Lett., 1997, 143.
33 L. Weber, Eur. J. Inorg. Chem., 2000, 2425.
34 F. Mathey, Chem. Rev., 1990, 90, 997.
35 J. Foerstner, A. Kakoschke, D. Stellfeld, H. Butenschön and R. Wartho, Organometallics, 1998, 17, 893.
36 J. Simon, G. J. Reiß, U. Bergsträßer, H. Heydt and M. Regitz, Eur. J. Inorg. Chem., 2001, 2067.
37 A. Jayaraman and B. T. Sterenberg, Organometallics, 2013, 32, 745.
38 M. Sanchez, R. Réau, C. J. Marsden, M. Regitz and G. Bertrand, Chem. – Eur. J., 1999, 1, 274.
39 L. L. Liu, J. Zhou, Y. Kim, L. L. Cao and D. W. Stephan, Dalton Trans., 2019, 48, 14242.
40 G. Maier, K.-A. Schneider, K.-D. Malsch, H. Irngartinger and A. Lenz, Angew. Chem., Int. Ed. Engl., 1982, 21, 437.