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A Molecular Precursor to Phosphaethyne and its Application in Synthesis of the Aromatic 1,2,3,4-Phosphatriazolate Anion

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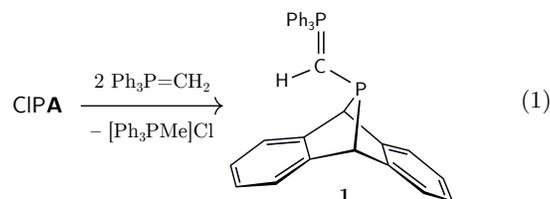
Abstract: Dibenzo-7-phosphanorbornadiene Ph₃PC(H)PA (**1**, **A** = C₁₄H₁₀, anthracene) is reported here as a molecular precursor to phosphaethyne (HC≡P), produced together with anthracene and triphenylphosphine. HCP generated by thermolysis of **1** has been observed by molecular beam mass spectrometry (MBMS), laser-induced fluorescence (LIF), microwave spectroscopy, and nuclear magnetic resonance (NMR) spectroscopy. In toluene, fragmentation of **1** has been found to proceed with activation parameters of $\Delta H^\ddagger = 25.5$ kcal/mol and $\Delta S^\ddagger = -2.43$ e.u., and is accompanied by formation of an orange insoluble precipitate. Results from computational studies of the mechanism of HCP generation are in good agreement with experimental data. This high temperature method of HCP generation has pointed to new reaction chemistry with azide anion to produce the 1,2,3,4-phosphatriazolate anion, HCPN₃⁻, for which structural data have been obtained in a single-crystal X-ray diffraction study. Negative ion photoelectron spectroscopy has shown the adiabatic detachment energy for this anion to be 3.555(10) eV. The aromaticity of HCPN₃⁻ has been assessed using nucleus-independent chemical shift (NICS), quantum theory of atoms in molecules (QTAIM), and natural bond orbital (NBO) methods.

Unsaturated organophosphorus compounds are important to a wide range of chemical disciplines from synthesis¹ to astrochemistry,²⁻⁴ but their study has been limited by reduced stability in comparison with their nitrogen congeners. This is principally caused by the reluctance of phosphorus to participate in π -bonding interactions, rendering such bonds reactive in the absence of kinetically stabilizing bulky substituents.⁵ Without steric protection they are seldom isolable, often accessible only at high temperature⁶ or through electric discharge.⁷ These harsh methodologies are not typically amenable to synthetic chemistry, making necessary the development of alternate routes to such species. To this end, molecular precursors are an exciting avenue of pursuit, allowing for clean generation of small molecules at mild temperatures and enabling reaction chemistry not possible at the temperature extremes.

Our previous work on thermally activated molecular precursors has proven them to be a convenient entryway to reactive small molecule chemistry, such as that of P₂,^{8,9} AsP,¹⁰ phosphinidenes,¹¹ and dimethylgermylene.¹² Interested in

expanding our substrate scope, we identified HC≡P, known as phosphaethyne, phosphaacetylene, or methyldynephosphine, as an interesting target species that has recently been discovered in outer space.⁴ Early studies of this compound demonstrated moderate stability at low temperature, but fleeting existence under ambient conditions due to rapid polymerization.¹³ Several synthetic pathways to phosphaalkynes have been developed,^{14,15} but the chemistry of the parent derivative HCP has stagnated; in fact, we are only aware of a single experimental study on the reactivity of HCP.¹⁶ Herein, we report the synthesis of a molecular precursor to phosphaethyne based on fragmentation with concomitant formation of anthracene and triphenylphosphine. Further reactivity of HCP is demonstrated through its [3+2] cycloaddition reaction with the azide ion at elevated temperature to yield the aromatic heterocyclic anion HCPN₃⁻.

Inspired by several reports of ylide fragmentation to yield small molecules,¹⁷ we directed our efforts to substitution of CIPA (**A** = C₁₄H₁₀, anthracene) with methylenetriphenylphosphorane (Equation 1), effectively “sandwiching” phosphaethyne between anthracene and triphenylphosphine in a manner reminiscent of P₂A₂.⁹



Accordingly, we found treatment of CIPA with two equivalents of Ph₃PCH₂ at -35 °C in THF to yield Ph₃PC(H)PA

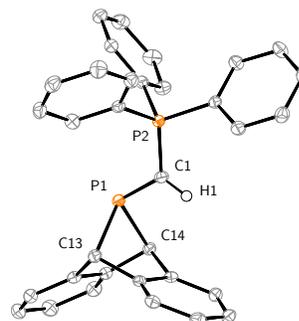


Figure 1. Molecular structure of **1** shown with 50% probability thermal ellipsoids. Solvent molecules and all hydrogen atoms except H1 are omitted for clarity. Selected interatomic distances [Å] and angles [°]: P1–C1 1.7442(15), P1–C13 1.9294(14), P1–C14 1.9412(15), P2–C1 1.6907(15); C1–P1–C13 108.08(7), C1–P1–C14 105.69(7), C13–P1–C14 77.92(6), P1–C1–P2 120.79(9).

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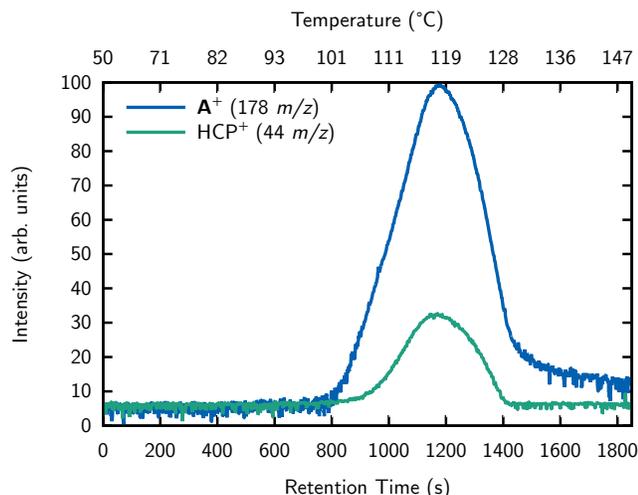


Figure 2. Molecular beam mass spectrometry (MBMS) of **1**.

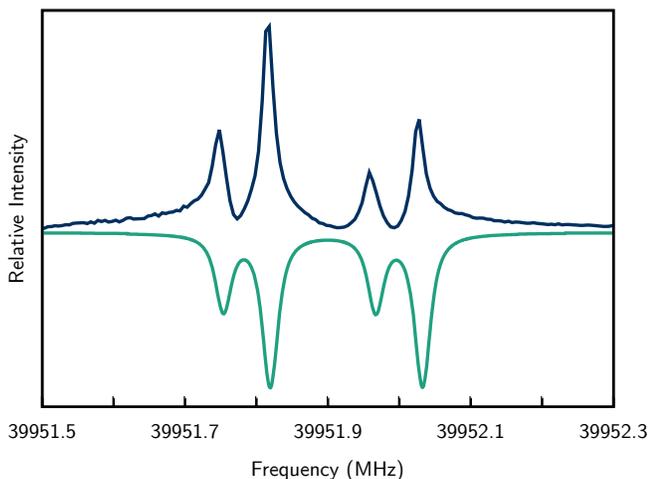


Figure 3. The $J = 1 \leftarrow 0$ rotational transition of phosphaethyne evolved by solid **1** at 95 °C. The microwave spectrum displays two hyperfine components from the ^{31}P nucleus ($I = 1/2$) and Doppler doubling. The lower inverted spectrum is a simulation generated with PGOPHER¹⁹ using previously reported rotational and coupling constants.²⁰

(**1**) along with insoluble $[\text{Ph}_3\text{PMe}]\text{Cl}$.¹⁸ The desired product could easily be separated from this precipitate by filtration, and isolated in 67% yield. The solid state structure of **1** (Figure 1) shares many characteristics with other RPA derivatives with elongated P1–C13 and P1–C14 bonds of 1.935 Å (avg) and an acute C13–P1–C14 angle of 77.92(6)° closely matching metrics reported for amino-substituted species.¹¹ Furthermore, the ylidic P2–C1 distance of 1.6907(15) Å is similar to that of Ph_3PCH_2 , reported to be 1.693 Å (avg).¹⁸

With successful preparation of **1**, we investigated its propensity to fragment thermally into phosphaethyne. Similar RPA architectures have allowed facile generation of transient phosphinidenes upon mild heating in benzene- d_6 ,¹¹ raising the question: is **1** capable of transient phosphinidene release, and might this phosphinidene $[\text{Ph}_3\text{P}=\text{C}(\text{H})\text{P}]$ subsequently break apart into PPh_3 and HCP?

Analysis of solid **1** by thermogravimetric analysis (TGA) revealed a mass-loss event centered about 115 °C suggesting HCP release. Conclusive identification of the evolved gas was obtained by molecular beam mass spectrometry (MBMS) (Figure 2).⁹ mass fragments corresponding to HCP (44 m/z) and anthracene (178 m/z) were simultaneously detected upon heating the solid to *ca.* 120 °C. Incorporation of a ^{13}C label at the ylidic carbon of **1** led to disappearance

of the mass fragment at 44 m/z and detection of a mass fragment at 45 m/z , in agreement with H^{13}CP generation. Gas evolved from **1** could be condensed into an NMR tube containing frozen diethyl ether to allow ^{31}P NMR analysis of HCP upon thawing and warming to –60 °C, matching the literature value (–32 ppm).²¹ The yield of HCP produced *via* vacuum transfer was 12% as quantified by ^{31}P NMR spectroscopy using an internal standard.

Molecular precursors to small molecules have been shown to have useful spectroscopic applications, allowing for selective generation of the species of interest in contrast to electric discharge or laser ablation methods.²² Upon thermolysis of solid **1**, microwave spectroscopy was successfully employed to detect the $J = 1 \leftarrow 0$ rotational transition of gaseous phosphaethyne at 39951.9 MHz as shown in Figure 3. The measured phosphorus spin–rotation coupling constant of 46(4) kHz showed excellent agreement with the literature value of 43.64(15) kHz.²⁰ Laser-induced fluorescence studies were performed using a resistively heated ceramic sample holder to heat **1** in a high vacuum chamber, revealing rotational transitions within the $\tilde{A}(03^1_1) \leftarrow \tilde{X}(00^0_0)$ band of HCP.²³ The estimated temperature of the gas was found to be 300 K, indicating any rotational excitation imparted to the HCP molecules during dissociation was relaxed by collisions with the chamber walls.

Having established the ability of **1** to evolve HCP upon mild thermal activation from the solid into the gas phase, we turned next to solution-phase investigations in order to probe for possible applications of **1** as an HCP source in synthesis. Heating a toluene solution of the precursor to 95 °C for 1.5 h successfully led to complete thermal fragmentation, depositing insoluble orange solids along with anthracene and triphenylphosphine in 51% and 56% yield, respectively, as quantified by ^1H NMR spectroscopy. The orange precipitate was not found to conform to a $(\text{HCP})_x$ empirical formula by combustion analysis, likely indicating partial incorporation of anthracenyl²⁴ or triphenylphosphoranyl moieties. Thus, thermolysis of **1** was not found to cleanly generate the previously reported phosphaethyne polymer,²⁵ an insoluble black solid¹³ formed with traces of P_4 .¹⁶

Monitoring the thermal decomposition of **1** in the absence of a chemical trap at several temperatures by ^1H and ^{31}P NMR spectroscopy allowed a kinetic analysis to be performed. The rate of decay of **1** followed first-order reaction kinetics, giving the rate constants listed in Table S.1. A fit to the Eyring equation gave parameters of $\Delta H^\ddagger = 25.5$ kcal/mol and $\Delta S^\ddagger = -2.43$ e.u. for thermolysis, consistent with a unimolecular process. No intermediates were observed by NMR spectroscopy during the thermolysis, including HCP, likely due to their fleeting stability at elevated temperatures.

Computational modeling was used to probe the mechanism of **1**'s fragmentation. The thermolysis was predicted to proceed as depicted in Figure 4, involving initial isomerization to a phosphirane, retro-[2+1]-cyclization to give a phosphinidene, and final ylide P–C bond scission to yield phosphaethyne. Similar isomerizations to three-membered rings have been postulated for other RPA derivatives as well as various silicon-based species.²⁶ Isomerization to the phosphirane intermediate is predicted to be rate-limiting with a transition state lying energetically uphill with $\Delta H^\ddagger = 27.8$ kcal/mol and $\Delta S^\ddagger = 1.9$ e.u., in agreement with solution-based experimental measurements. Initial PPh_3 release was found to be prohibitively endergonic with an acti-

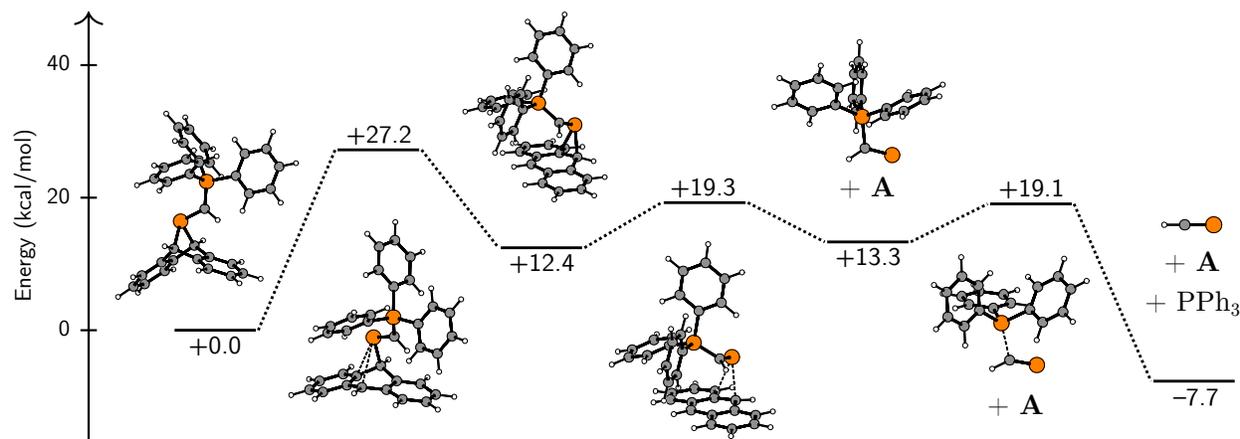
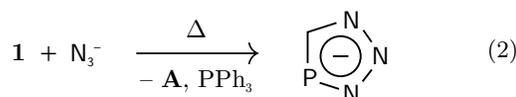


Figure 4. Gibbs free energies (in kcal/mol at 298.15 K) of intermediates and transition states predicted for thermal fragmentation of **1**.

vation barrier of $\Delta G^\ddagger = 72.7$ kcal/mol at 298.15 K.

With recent success preparing the $P_2N_3^-$ anion through “click reaction” of N_3^- and diphosphorus generated from P_2A_2 ,²⁷ we sought to probe reactivity of transient HCP with the azide anion to yield analogous $HCPN_3^-$ as shown in Equation 2.



Cycloaddition of phosphalkynes with organic azides and other 1,3-dipoles is well precedented,^{15,28} but such reactivity with inorganic azide to yield the parent 1,2,3,4-phosphatriazolate²⁹ anion has not been reported. Heating a THF solution of **1** with 7 equiv. tetra-*n*-butylammonium azide (TBAN₃) at 80 °C in a high-pressure vessel gave total consumption of **1** and 67% conversion to a new species with a chemical shift of 192 ppm by ³¹P NMR spectroscopy. Its identity was assigned to be $HCPN_3^-$ by comparison of the ¹H, ¹³C, and ³¹P NMR signatures of the new species in THF-*d*₈ with the similar spectroscopic signatures of $HCPN_3Me$,¹⁶ as well as those of [K-kryptofix-222][¹AdCPN₃], which we isolated from a 1:1:1 mixture of ¹AdCP, KN₃, and Kryptofix-222 in THF in 87% yield. Further, the parent $HCPN_3^-$ ion (86 *m/z*) was detected by negative-ion electrospray ionization mass spectrometry. The [3+2] cycloaddition chemistry between HCP and azide was computationally predicted to proceed with a modest activation barrier of $\Delta G^\ddagger = 14.4$ kcal/mol at 298.15 K (see SI).

Interestingly, this same cycloaddition chemistry was not successful by vacuum transfer of HCP onto a frozen TBAN₃ slurry in THF. Insoluble brown solids rapidly developed upon warming the mixture to -78 °C, even before the THF

could thaw fully. This rapid polymerization was not observed in the absence of TBAN₃, pointing to nucleophilic azide acting as a polymerization initiator. Cycloaddition of HCP with methyl azide has been reported under these conditions,¹⁶ but the low solubility of TBAN₃ at -78 °C in aprotic solvents and the relatively high concentration of HCP provided by vacuum transfer seem to preclude cycloaddition chemistry in favor of polymerization. This points to **1** enabling new transformations of HCP unattainable by traditional vacuum transfer techniques through the gradual release and low concentration of HCP generated by its thermalolysis.

Pure $HCPN_3^-$ was obtained by heating **1** with tris(dimethylamino)sulfonium azide (TASN₃) in THF at 85 °C for 3 h, allowing isolation of [TAS][$HCPN_3^-$] in 14% yield. Diffraction quality crystals were grown by slow vapor diffusion of diethyl ether into a saturated acetonitrile solution at -35 °C to give the structure shown in Figure 5. The lack of positional disorder in the anion was likely influenced by two weak cation-anion interactions³⁰ marked by dashed lines with N···H distances of 2.615 Å (avg). The bond metrics of the $HCPN_3^-$ anion match closely to those of ¹AdCPN₃⁻ (see SI Figure S.20), and all ring interatomic distances demonstrate bond lengths intermediate between single and double bonds,³¹ pointing to electron delocalization.

Characterization of the $HCPN_3^-$ heterocycle by negative ion photoelectron spectroscopy (NIPES) revealed its adiabatic detachment energy (electron affinity of $HCPN_3^\bullet$) to be 3.555(10) eV. This value is intermediate between that of 1,2,3-triazolate and $P_2N_3^-$, 3.447(4) eV³² and 3.765(10) eV³³ respectively, but is much different from the values of the aromatic anions $C_5H_5^-$ ³⁴ and P_5^- .³⁵

A computational evaluation of aromaticity criteria for $HCPN_3^-$ was performed in comparison with six other 6 π aromatic five-membered rings: $C_5H_5^-$, $C_2H_2N_3^-$ (1,2,3-triazolate), $N_2S_3^{2+}$, N_5^- , $P_2N_3^-$, and P_5^- . The profile of the nucleus-independent chemical shift along the *z* axis (NICS_{zz}) shows the largest magnitude at *ca.* 0.7 Å above the ring critical point,³⁶ and analysis of the π orbital contribution to the magnetic susceptibility by quantum theory of atoms in molecules (QTAIM) theory reveals 51% contribution.³⁷ Both criteria are characteristic of an aromatic ring system, and further analysis by natural bond orbital (NBO) methods reveal extensive delocalization as shown in Figure 6. By all measures, the aromaticity of $HCPN_3^-$ seems in line with the other 6 π systems of comparison, and appears in-

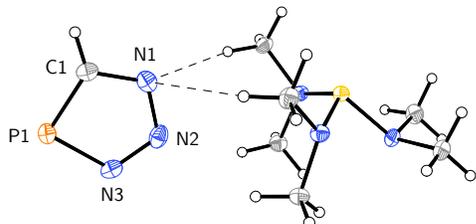


Figure 5. Molecular structure of [TAS][$HCPN_3^-$] shown with 50% probability thermal ellipsoids. Selected interatomic distances [Å] and angles [°] for $HCPN_3^-$: C1-P1 1.7216(12), P1-N3 1.6838(11), N2-N3 1.3279(15), N1-N2 1.3465(15), C1-N1 1.3400(16); C1-P1-N3 89.54(6), P1-N3-N2 111.97(8), N3-N2-N1 114.90(10), N2-N1-C1 111.56(10), N1-C1-P1 112.03(9).

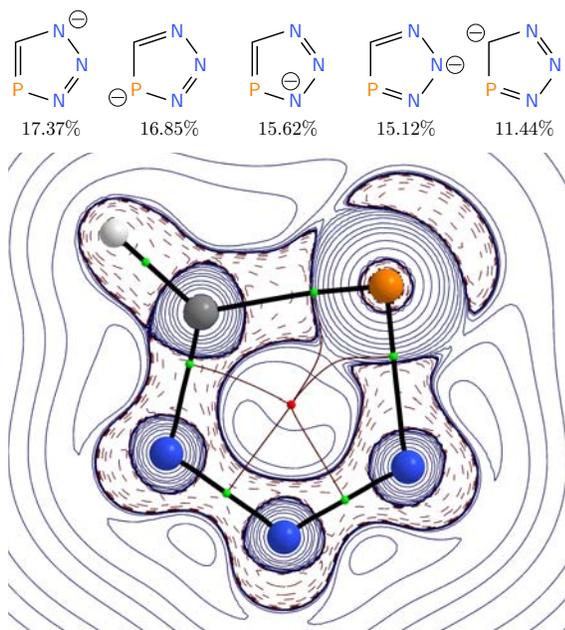


Figure 6. An NBO analysis of HCPN_3^- provides natural resonance theory (NRT) weights (*top*). The Laplacian of the electron density within the plane of HCPN_3^- (*bottom*) shows accumulation and depletion of density.

intermediate between that of the 1,2,3-triazolate and P_2N_3^- anions.

The confirmation of phosphacetyne release from **1** further demonstrates the utility of well defined molecular precursors for the clean and mild generation of interesting small molecules. Additional synthetic modifications of **1** and similar precursors are likely to allow for spectroscopic characterization of species currently unknown in the cosmos, giving astrochemists the proper information to search for their presence. Furthermore, the successful reactivity of HCP with azide to yield HCPN_3^- proves the ability of rationally designed molecular precursors to promote reaction chemistry beyond that of traditional means.

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Supporting Information Available: Experimental details, characterization data, X-ray crystallographic information, computational details, and tables of Cartesian coordinates are provided in the Supporting Information document. This material is available free of charge via the Internet at <http://pubs.acs.org/>.

References

- (1) Regitz, M.; Scherer, O. J. *Multiple Bonds and Low Coordination in Phosphorus Chemistry*, 1st ed.; Thieme Publishing Group, 1990; pp 1–32.
- (2) (a) Frebel, A. *Daedalus* **2014**, *143*, 71; (b) Cummins, C. C. *Daedalus* **2014**, *143*, 9.

- (3) Tenenbaum, E. D.; Woolf, N. J.; Ziurys, L. M. *Astrophys. J.* **2007**, *666*, L29.
- (4) Milam, S. N.; Halfen, D. T.; Tenenbaum, E. D.; Apponi, A. J.; Woolf, N. J.; Ziurys, L. M. *Astrophys. J.* **2008**, *684*, 618.
- (5) Cowley, A. H.; Jones, R. A.; Mardones, M. A. Phosphorus Atoms in Unusual Environments. In *Phosphorus Chemistry*; ACS Symposium Series 486; ACS, 1992; pp 56–63.
- (6) Scherer, O. J. *Angew. Chem. Int. Ed.* **2000**, *39*, 1029.
- (7) (a) Mielke, Z.; Brabson, G. D.; Andrews, L. J. *Phys. Chem.* **1991**, *95*, 75; (b) Holtz, D.; Beauchamp, J. L.; Eyley, J. R. *J. Am. Chem. Soc.* **1970**, *92*, 7045.
- (8) Piro, N. A.; Figueroa, J. S.; McKellar, J. T.; Cummins, C. C. *Science* **2006**, *313*, 1276.
- (9) Velian, A.; Nava, M.; Temprado, M.; Zhou, Y.; Field, R. W.; Cummins, C. C. *J. Am. Chem. Soc.* **2014**, *136*, 13586.
- (10) Spinney, H. A.; Piro, N. A.; Cummins, C. C. *J. Am. Chem. Soc.* **2009**, *131*, 16233.
- (11) Velian, A.; Cummins, C. C. *J. Am. Chem. Soc.* **2012**, *134*, 13978.
- (12) Velian, A.; Transue, W. J.; Cummins, C. C. *Organometallics* **2015**, *34*, 4644.
- (13) Gier, T. E. *J. Am. Chem. Soc.* **1961**, *83*, 1769.
- (14) (a) Cooper, T. A.; Kroto, H. W.; Nixon, J. F.; Ohashi, O. *Chem. Commun.* **1980**, 333; (b) Pellerin, B.; Denis, J.-M.; Perrocheau, J.; Carrie, R. *Tetrahedron Lett.* **1986**, *27*, 5723; (c) Guillemain, J.-C.; Janati, T.; Denis, J. M.; Guenot, P.; Savignac, P. *Angew. Chem. Int. Ed. Engl.* **1991**, *30*, 196; (d) Le Floch, P.; Mathey, F. *Chem. Commun.* **1993**, 1295; (e) Guillemain, J.-C.; Janati, T.; Denis, J.-M. *J. Org. Chem.* **2001**, *66*, 7864; (f) Figueroa, J. S.; Cummins, C. C. *J. Am. Chem. Soc.* **2004**, *126*, 13916.
- (15) Regitz, M. *Chem. Rev.* **1990**, *90*, 191.
- (16) Fuchs, E. P. O.; Hermesdorf, M.; Schnurr, W.; Rösch, W.; Heydt, H.; Regitz, M.; Binger, P. *J. Organomet. Chem.* **1988**, *338*, 329.
- (17) (a) Matern, E.; Fritz, G.; Pikies, J. Z. *Anorg. Allg. Chem.* **1997**, *623*, 1769; (b) Canac, Y.; Conejero, S.; Soleilhavoup, M.; Donnadiou, B.; Bertrand, G. *J. Am. Chem. Soc.* **2006**, *128*, 459; (c) Wasylenko, W. a.; Kebede, N.; Showalter, B. M.; Matsunaga, N.; Miceli, A. P.; Liu, Y.; Ryzhkov, L. R.; Hadad, C. M.; Toscano, J. P. *J. Am. Chem. Soc.* **2006**, *128*, 13142; (d) Chivers, T.; Oakley, R. T.; Cordes, A. W.; Sweptson, P. J. *Chem. Soc., Chem. Commun.* **1980**, 2, 35.
- (18) Schmidbaur, H.; Jeong, J.; Schier, A.; Graf, W.; Wilkinson, D. L.; Müller, G.; Krüger, C. *New J. Chem.* **1989**, *13*, 341.
- (19) PGOPHER, a Program for Simulating Rotational, Vibrational and Electronic Structure, C. M. Western, University of Bristol, <http://pgopher.chm.bris.ac.uk>.
- (20) (a) Bizzocchi, L.; Thorwirth, S.; Müller, H. S. P.; Lewen, F.; Winnewisser, G. *J. Mol. Spectrosc.* **2001**, *205*, 110; (b) Bizzocchi, L.; Esposti, C. D.; Dore, L.; Puzzarini, C. *Chem. Phys. Lett.* **2005**, *408*, 13.
- (21) Anderson, S. P.; Goldwhite, H.; Ko, D.; Letsou, A.; Esparza, F. *Chem. Commun.* **1975**, 744.
- (22) Corrie, J. E. T.; Kirby, G. W.; Laird, A. E.; Mackinnon, L. W.; Tyler, J. K. *J. Chem. Soc., Chem. Commun.* **1978**, 275.
- (23) Johns, J. W. C.; Shurvell, H. F.; Tyler, J. K. *Can. J. Phys.* **1969**, *47*, 893–920.
- (24) Annen, U.; Regitz, M. *Tetrahedron Lett.* **1987**, *28*, 5141.
- (25) Hölzl, T.; Veszprémi, T.; Nguyen, M. T. *C. R. Chimie* **2010**, *13*, 1173.
- (26) (a) Velian, A. Taming Reactive Phosphorus Intermediates with Organic and Inorganic Carriers. Ph.D. thesis, MIT, 2015; (b) Lim, Y. M.; Lee, M. E.; Lee, J.; Do, Y. *Organometallics* **2008**, *27*, 6375; (c) Gerdes, C.; Saak, W.; Haase, D.; Müller, T. J. *Am. Chem. Soc.* **2013**, *135*, 10353.
- (27) Velian, A.; Cummins, C. C. *Science* **2015**, *348*, 1001.
- (28) Fehlhammer, W. P.; Beck, W. Z. *Anorg. Allg. Chem.* **2015**, *641*, 1599.
- (29) Also known as 1,2,3,4-triazaphospholide; Sklorz, J. A. W.; Müller, C. *Eur. J. Inorg. Chem.* **2016**, 595.
- (30) Weinhold, F.; Klein, R. a. *Mol. Phys.* **2012**, *110*, 565.
- (31) Pyykkö, P.; Atsumi, M. *Chem. Eur. J.* **2009**, *15*, 12770.
- (32) Ichino, T.; Andrews, D. H.; Rathbone, G. J.; Misaizu, F.; Calvi, R. M. D.; Wren, S. W.; Kato, S.; Bierbaum, V. M.; Lineberger, W. C. *J. Phys. Chem. B* **2008**, *112*, 545.
- (33) Hou, G.-L.; Chen, B.; Transue, W. J.; Hrovat, D. A.; Cummins, C. C.; Borden, W. T.; Wang, X.-B. *Chem. Sci.*, **2016**, DOI: 10.1039/c5sc04667j.
- (34) Ichino, T.; Wren, S. W.; Vogelhuber, K. M.; Gianola, A. J.; Lineberger, W. C.; Stanton, J. F. *J. Chem. Phys.* **2008**, *129*, 084310.
- (35) Zhai, H.-J.; Wang, L.-S.; Kuznetsov, A. E.; Boldyrev, A. I. *J. Phys. Chem. A* **2002**, *106*, 5600.
- (36) Stanger, A. *J. Org. Chem.* **2006**, *71*, 883.
- (37) Foroutan-Nejad, C. *J. Phys. Chem. A* **2011**, *115*, 12555.

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