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Phosphinecarboxamide: A Phosphorus-Containing Analogue of Urea and Stable Primary Phosphine

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Supporting Information

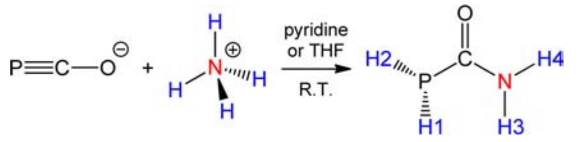
ABSTRACT: Reactions of the 2-phosphaethynolate anion (PCO^-, **1**) with ammonium salts quantitatively yielded phosphinecarboxamide ($PH_2C(O)NH_2$, **2**). The molecular structure and chemical properties of **2** were studied by single-crystal X-ray diffraction and multielement NMR spectroscopy. This phosphorus-containing analogue of urea is a rare example of an air-stable primary phosphine.

Wöhler's synthesis of urea is a scientific milestone considered by many as the birth of modern organic chemistry.[1,2] Prior to this discovery, the synthesis of organic chemicals (such as urea) using inorganic materials (e.g., silver cyanate and ammonium chloride) was entirely unprecedented. At the very least this finding served to blur boundaries between disparate scientific disciplines, while some regard it as the beginning of the end for the theory of *vitalism*.[2] It is worthy of mention however, that this discovery, as with many paradigm-shifting ones before and after, was entirely serendipitous and that Wöhler's original goal was to isolate ammonium cyanate. He and von Liebig achieved this objective soon thereafter,[3] although the structure of the solid was not determined until 2003 (173 years after the original report).[4] These historic observations inspired us to explore possible chemical similarities between cyanate ($N{\equiv}C{-}O^-$) and its heavier congener, the 2-phosphaethynolate ion ($P{\equiv}C{-}O^-$, **1**). Our studies have resulted in the synthesis of the unprecedented phosphinecarboxamide ($PH_2C(O)NH_2$, **2**), a heavier analogue of urea where one of the primary amine groups ($-NH_2$) is replaced by a phosphine ($-PH_2$). Phosphinecarboxamide (or carbamoylphosphine), **2**, exhibits remarkable air- and moisture stability (it can be synthesized in water, and its half-life in a pyridine-d_5 solution exposed to air is approximately 9 days). Such air-stability is a highly unusual trait for a primary phosphine.[5]

The 2-phosphaethynolate ion, **1**, was first reported by Becker and co-workers in 1992 and has been the subject of limited study in the ensuing years (presumably due to the technical difficulties associated with its synthesis).[6,7] Recently, two separate reports by Grützmacher and Cummins revived interest in this remarkable anionic species.[8,9] For instance, Grützmacher's synthesis has allowed for the reactivity of **1** toward transition metals and CO_2 to be explored for the first time.[10,11] Our research group has recently observed that **1** can be obtained by direct carbonylation of solutions of K_3P_7 in moderate to good yields.[12] This observation has allowed us to explore fundamental aspects of the chemistry of this remarkable anion such as its [2 + 2] cycloaddition chemistry toward heteroallenes. We now report that solutions of [K(18-crown-6)][**1**] react with simple ammonium salts NH_4X (X = BPh_4, Cl) to afford **2** in quantitative yields (see Supporting Information [SI] for synthetic methods). This reaction is analogous to Wöhler's urea synthesis, the mechanism of which has been studied computationally and is postulated to involve protonation of the anion followed by interaction of ammonia with the resulting acid.[13] The synthesis of derivatized carbamoylphosphines (e.g., $Ph_2PC(O)NH_2$) by reaction of isocyanic acid with phosphines was reported in the literature in the late 1960s; however, to our knowledge, no attempts were made to synthesize the parent protic species, **2**, from reaction of PH_3 with isocyanic acid.[14] More recently, the catalytic hydrophosphination of isocyanates with secondary phosphines has also been shown to afford novel phosphinecarboxamides ($R_2PC(O)NHR'$; R = Ph, 4-$MeOC_6H_4$, 4-MeC_6H_4; R′ = Ph, Cy, Ad, 1-Naph and C_6H_4X-4 where X is F, Cl, Br, OMe, CF_3); however, this method only allows for the synthesis of tertiary phosphines.[15]

In a typical reaction, a solid sample of [K(18-crown-6)][**1**] was dissolved alongside NH_4X (X = BPh_4, Cl) in a 1:1 molar ratio (see Scheme 1). The reaction time required for full conversion to **2** was found to be strongly dependent on the solubility of the ammonium salt employed. When using NH_4BPh_4, removal of the resulting [K(18-crown-6)]BPh_4 salt is possible by means of trap-to-trap distillation as **2** is a liquid at room temperature (presumably a result of its reduced hydrogen-bonding ability relative to urea). Interestingly however, when employing a halide salt such as NH_4Cl, **2** forms a sufficiently strong hydrogen-bonding interaction with the anion that purification by distillation is not viable. This is perhaps unsurprising, considering the prominent role of urea-based receptors in anion binding.[16]

Scheme 1. Synthesis of 2 from Reaction of 1 with NH_4X Salts (X = BPh_4, Cl)



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The ^{31}P NMR spectrum of **2** in pyridine-d_5 reveals a triplet of doublets at −134.4 ppm ($^1J_{P-H}$ = 209 Hz, $^3J_{P-H}$ = 12 Hz) which collapses to a singlet on proton decoupling. The room-temperature ^1H NMR spectrum reveals a doublet centered at 3.82 ($^1J_{P-H}$ = 209 Hz) in addition to two broad resonances at 8.57 and 9.05 ppm (which integrate in a 2:1:1 ratio, respectively). The doublet at 3.82 ppm in the proton spectrum collapses to a singlet on selective decoupling of the ^{31}P NMR resonance at −134.4 ppm. The two broad resonances at 8.57 and 9.04 ppm coalesce to a singlet at temperatures above 75 °C (however, prolonged heating ultimately results in sample decomposition to PH_3 and isocyanic acid). These data are consistent with free rotation around the P−C bond and a planar arrangement, with restricted rotation, around the sp^2-hybridized nitrogen atom (rendering both amide protons inequivalent; $^3J_{P-H}$ coupling to the *cis* proton of the amine substituent, H3 in Scheme 1, is too weak to be resolved experimentally). Finally, the $^{13}C\{^1H\}$ NMR spectrum reveals the presence of a doublet at 175.8 ppm ($^1J_{P-C}$ = 8 Hz). Computed spin−spin coupling values for **2** are generally in good agreement with these experimentally determined values (computed values: $^1J_{P-H}$ = 167 Hz; $^3J_{P-H}$ = 7 Hz; $^1J_{P-C}$ = −32 Hz). Selected spectra for **2** are represented in Figure 1, while full spectra can be found in the SI.

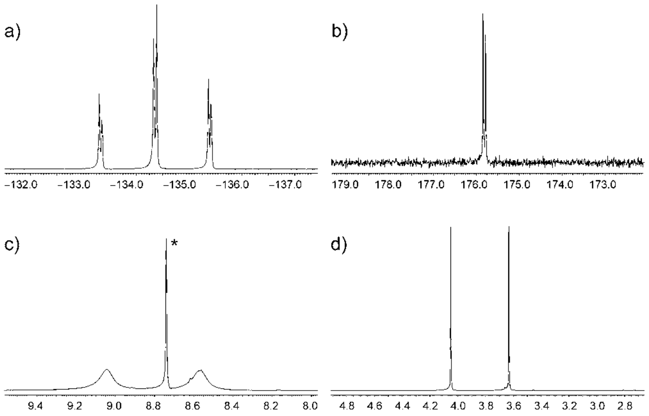


Figure 1. Selected regions of the NMR spectra for a pyridine-d_5 solution of **2**. (a) ^{31}P NMR spectrum (this resonance collapses to a singlet on proton decoupling). (b) Carbonyl region of the $^{13}C\{^1H\}$ NMR spectrum. (c) N−H region of the ^1H NMR spectrum (resonance labeled with an * arises from residual protic pyridine). (d) P−H region of the ^1H NMR spectrum (this resonance collapses to a singlet on selective broadband decoupling of the phosphorus resonance at −134.4 ppm). All chemical shifts given in ppm.

Isotopic labeling of **2** using $^{15}NH_4Cl$ allowed us to assign the most upfield amine resonance in the ^1H NMR spectrum as the *trans* position relative to the phosphorus atom (H4, doublet of doublets: $^1J_{N-H}$ = 85 Hz; $^3J_{P-H}$ = 12 Hz). The most downfield amine resonance appears as a doublet ($^1J_{N-H}$ = 89 Hz). The $^{31}P\{^1H\}$ NMR spectrum of $PH_2C(O)^{15}NH_2$ reveals a doublet with a $^2J_{P-N}$ coupling constant of 12 Hz. Deuterium labeling using ND_4Cl to give $PD_2C(O)ND_2$ reveals a 1:2:3:2:1 multiplet in the $^{31}P\{^1H\}$ NMR spectrum with a $^1J_{P-D}$ of 31 Hz as would be anticipated considering the different gyromagnetic ratios of ^2H and ^1H ($\gamma_H/\gamma_D \approx 6.5$).[17]

Species **2** was crystallographically characterized by exploiting its hydrogen-bonding ability alongside half of an 18-crown-6 molecule in **2**·0.5(18-crown-6).[18] The mixture crystallizes in space group $P\bar{1}$ (No. 2) with the 18-crown-6 molecule located on a center of inversion. The phosphinecarboxamide moiety, **2** (Figure 2), displays a pyramidalized geometry at the phosphorus atom, P1, with a planar carboxamide moiety (deviation from planarity for P1/C1/O1/N1/H3/H4: 0.03 Å). This observation is supported by room-temperature NMR spectroscopic data (*vide supra*) and consistent with significant delocalization of *π* electron density between the carbonyl and amide groups, with no significant *π*-interactions arising between the phosphine lone pair and the carbonyl carbon. In other words, of the resonance canonicals that are depicted for **2** in Scheme 2, the most significant contributions are from **2**(i) and **2**(ii). Bond metric data for **2** also support this observation: the P−C bond is 1.865(1) Å which is comparable to the sum of

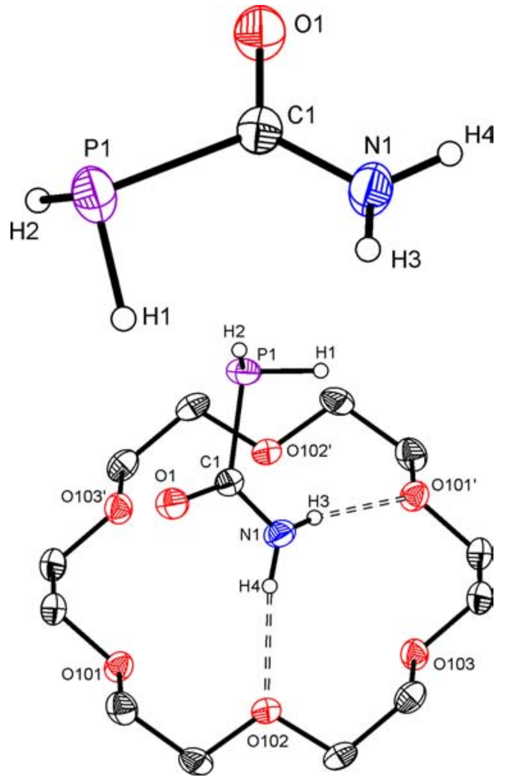
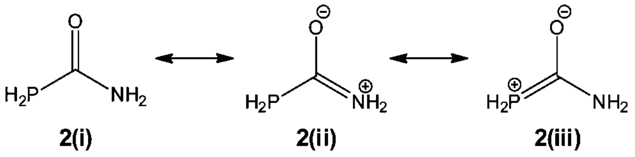


Figure 2. Molecular structure of **2**·0.5(18-crown-6). Top: the phosphinecarboxamide moiety. Bottom: depiction of the hydrogen-bonding interactions arising between **2** and 18-crown-6 (hydrogen atoms of the crown ether removed for clarity). Anisotropic thermal displacement ellipsoids are pictured at the 50% probability level. Hydrogen atom positions were refined isotropically and are pictured as spheres of arbitrary radius. Selected bond distances (Å) and angles (deg): P1−C1: 1.865(1); P1−H1: 1.27(2); P1−H2: 1.30(2); C1−O1: 1.230(2); C1−N1: 1.329(2); N1−H3: 0.85(2); N1−H4: 0.88(2); H3···O101′: 2.22(2); H4···O102: 2.09(2); P1−C1−O1: 118.5(1); P1−C1−N1: 117.3(1); O1−C1−N1: 124.1(1). Symmetry operation: 1 − *x*, −*y*, 1 − *z*.

Scheme 2. Possible Resonance Forms for 2



single bond covalent radii for the elements (1.80−1.86 Å).[19] The C−O and C−N bond distances are 1.230(2) and 1.329(2) Å, respectively, and are consistent with other carboxamides in the literature.[20] Short H···O hydrogen-bonding contacts (2.22(2) and 2.09(2) Å) were observed between the N−H protons and oxygen atoms of the 18-crown-6. The IR spectrum of a Nujol mull of **2**·0.5(18-crown-6) reveals an intense C=O stretching band at 1650 cm^{-1}. Further bands arising from NH_2 stretching (3406, 3318 cm^{-1}) and bending modes (1607 cm^{-1}), and the C−N stretching mode (1104 cm^{-1}) were also clearly identifiable. The P−H stretching modes were observed at 2352 and 2302 cm^{-1}.

Density functional theory (DFT) level calculations support the aforementioned observations. The optimized computed geometry of **2** is in excellent agreement with that determined crystallographically (see SI for a comparison of bond metric data). The only notable difference is that the computed N−H and P−H bonds are, on average, 0.12 Å longer than those determined by single-crystal X-ray diffraction. The discrepancy arises from the involvement of the H 1s electron in bonding, which results in a localization of electron density between the heteroelement and the H atom (such a notable asymmetric distribution of electron density about the H nucleus is manifested in unrealistically short E−H bonds in X-ray structures).[21] The optimized geometry is pyramidal at the phosphorus atom with the barrier to inversion computed to be 112.71 kJ mol^{-1} (in line with previous reports for phosphines).[22,23] The HOMO has significant lone-pair character on the phosphorus atom (44.38% P), although the p_z orbital (with the z axis defined as orthogonal to the $PC(O)NH_2$ plane) also contributes to other lower-energy π-orbitals HOMO−1, HOMO−2, and HOMO−5 (the HOMO−3 and HOMO−4 are mainly of P−H and P−C σ-bonding character, respectively). The large computed HOMO−LUMO energy gap (6.62 eV) and significant mixing of π-orbitals may account for the stability of **2** relative to other much more air-sensitive primary phosphines. It is interesting to note, however, that extensive π-delocalization of the phosphine lone-pair (and/or a lack of phosphorus lone pair character at the HOMO) does not seem to contribute to the relative air stability of **2** as has been observed for other primary phosphines.[24]

In conclusion, extending the principles of Wöhler's synthesis of urea to the chemistry of the phosphaethynolate anion has allowed us to access a novel small molecule of enormous fundamental importance, $PH_2C(O)NH_2$. We have also obtained important structural and spectroscopic data for the simplest member of a family of species that may ultimately be used in coordination chemistry, anion sensing, and the synthesis of novel materials such as phosphorus-containing resins. Studies are currently ongoing to extend the synthetic scope of this reaction to other ammonium and phosphonium salts.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Full experimental details, single-crystal X-ray diffraction data, NMR and IR spectra, and computational details. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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(18) Crystallographic data for **2**·0.5(18-crown-6): formula $C_7H_{16}NO_4P$; triclinic, $P\bar{1}$ (No. 2); a = 8.4093(2) Å, b = 8.6581(3) Å, c = 8.7267(3) Å, α = 105.959(1)°, β = 114.847(2)°, γ = 96.574(1)°, V = 534.73(3) $Å^3$; Z = 2; T = 150(2) K; ρ_{calc} = 1.299 g cm^{-3}; μ = 0.243 mm^{-1}; 6640 reflections collected; 2418 independent reflections; R(int) = 0.0248; R1/wR2 = 3.21/7.81% for the observed data ($I \geq 2\sigma(I)$); R1/wR2 = 4.16/8.21% for all the data; GOF = 1.046.

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