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A stable primary phosphane oxide and its heavier congeners

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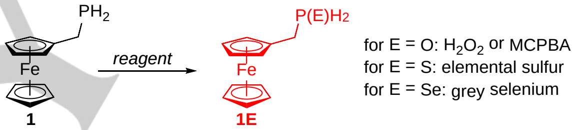
Abstract: (Ferrocenylmethyl)phosphane (**1**) oxidation with hydrogen peroxide, elemental sulfur and grey selenium produced (ferrocenylmethyl)phosphane oxide **1O**, sulfide **1S** and selenide **1Se**, respectively, as the first *isolable* primary phosphane chalcogenides lacking steric protection. At elevated temperatures, compound **1O** disproportionated into **1** and (ferrocenylmethyl)phosphinic acid. In reactions with [(η^6-mes)$RuCl_2$]$_2$, **1O** underwent tautomerization into a phosphane complex [(η^6-mes)$RuCl_2${$FcCH_2PH(OH)$-κP}], whereas **1S** and **1Se** lost their P-bound chalcogen atoms, giving rise to the phosphane complex [(η^6-mes)$RuCl_2$($FcCH_2PH_2$-κP)] (Fc = ferrocenyl, mes = mesitylene). No tautomerization was observed in the reaction of **1O** with $B(C_6F_5)_3$, which instead produced a Lewis pair $FcCH_2P(O)H_2{-}B(C_6F_5)_3$. Phosphane oxide **1O** added to C=O bonds of aldehydes and ketones and even to cumulenes PhNCE (E = O and S). However, both PH hydrogens were only employed in the reactions with aldehydes and cyanates.

Despite unrelenting research efforts, the chemistry of organophosphorus compounds still poses major challenges. For instance, although the long-sought air-stable and isolable primary phosphanes without substantial steric protection have been already reported,[1,2] the corresponding *primary* phosphane chalcogenides continue to elude chemists.[3,4] To the best of our knowledge, primary phosphane oxides have only been generated or postulated in reaction mixtures so far,[5] with the sole exception of the highly unstable *n*-octylphosphane oxide,[6] and their stable congeners with heavier chalcogen atoms have never been reported at all.[7] Yet, considering the remarkable influence of the ferrocenylmethyl group on the overall chemical stability[8] of the primary phosphane $FcCH_2PH_2$ (**1**; Fc = ferrocenyl),[9] we hypothesized that the corresponding phosphane oxide, $FcCH_2P(O)H_2$ (**1O**), could be stabilized and even isolated. Accordingly, in this contribution, we describe the isolation of the bench-stable primary phosphane oxide **1O**, the analogous phosphane sulfide (**1S**) and the first primary phosphane selenide (**1Se**).

For this purpose, the starting phosphane **1** was synthesized by an alternative, three-step procedure from ferrocene carboxaldehyde (see the Supporting Information). Subsequent oxidation of **1** with hydrogen peroxide (10 equiv. of H_2O_2, methanol/CH_2Cl_2 at 0°C for less than 10 min, 80% yield; Scheme 1) or with 3-chloroperoxybenzoic acid (MCPBA; 1 equiv. in dichloromethane at 0°C; 90% yield) cleanly and swiftly produced the phosphane oxide **1O**. This compound was isolated by a conventional chromatography as an air-stable, yellow solid with a characteristic though not intense smell of phosphane. Compound **1O** could be stored under ambient conditions but, upon heating to 100°C in a solution, it disproportionated into **1** and (ferrocenylmethyl)phosphinic acid (**2**) (see Equation 1):

$$2FcCH_2P(O)H_2\ (\mathbf{1O}) \rightarrow \mathbf{1} + FcCH_2P(O)OH\ (\mathbf{2}) \qquad \text{Eq. 1}$$

Acid **2** also formed when **1** was treated with an excess of MCPBA (2 equiv.); similar over-oxidation with H_2O_2 was only noted over extended reaction times.



Scheme 1. Synthesis of P-chalcogenides **1E**

The synthesis of the corresponding phosphane sulfide **1S** was rather difficult due to the thermal sensitivity of **1S** (decomposition above 50°C) and to its tendency to enter into follow-up reactions, producing mixtures of polythionated compounds. When using 10 equiv. of sulfur (in benzene at 50°C for 1 day), the reaction mixture contained 8% of the starting phosphane, 61% of **1S** and 31% of other unidentified products. From this mixture, nevertheless, **1S** could be isolated in a 30% yield as a yellow solid, which was stable under inert atmosphere but gradually decomposed when exposed to air. Thionation of **1** or **1O** with Lawesson reagent proceeded similarly. In contrast, **1Se** was prepared smoothly as the sole product of the reaction between **1** and grey selenium (1.5 equiv. of Se in toluene at 50°C overnight) and isolated in a 93% yield as a yellow, extremely malodorous solid. Under inert atmosphere, the compound could be stored practically indefinitely, albeit gradually converting into **1**, **2** and red selenium when exposed to air and moisture. Unlike its lighter congeners, **1Se** did not decompose when heated to 100°C for 2 days (in CH_2Cl_2/hexane under argon), but failed to provide crystalline samples. Our attempts at chalcogenation of **1** with elemental tellurium under otherwise similar conditions failed, only producing some **2**.

Compounds **1O**, **1S** and **1Se** are reluctant to crystallize, and their formulation was thus mostly based on spectroscopic methods. In their ^{31}P NMR spectra, they displayed triplets of triplets due to interactions of the phosphorus atom with two directly bonded hydrogen atoms and with the protons of the adjacent CH_2 group. In proton-decoupled spectra, these signals collapsed into singlets (for parameters, see Table S5). The presence of PH hydrogens was also indicated by ^1H NMR spectra, showing a doublet of triplets resulting from their interaction with ^{31}P and with the methylene protons. The spectra of **1Se** further contained characteristic ^{77}Se satellites (Figure 1). The $^1J_{PSe}$ coupling constant (733 Hz) of **1Se** was larger than that of the tertiary phosphane selenide $FcCH_2P(Se)Ph_2$ (728 Hz), hence suggesting that the basicity of **1** is lower than that of $FcCH_2PPh_2$.[10]

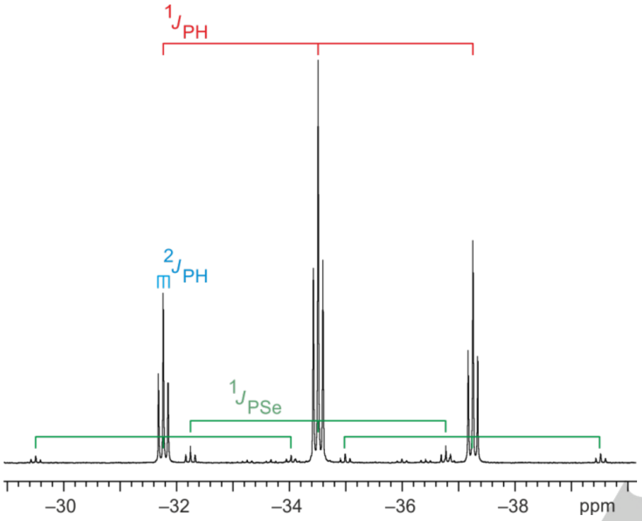
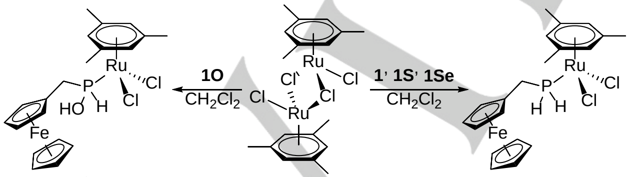


Figure 1. ^{31}P NMR spectrum of **1Se** (162 MHz, $CDCl_3$)

Notably, no signs of phosphinous acid tautomer were observed in the NMR spectra of **1O** recorded in common deuterated solvents (even after adding 1,8-bis(dimethylamino)naphthalene as a proton scavenger). Nevertheless, a facile tautomerization[11] occurred during the reaction of **1O** with [(η^6-mesitylene)RuCl(μ-Cl)]$_2$, producing complex **3** as the sole product (Scheme 2).[12] Unexpectedly, similar reactions with **1S** and **1Se** took an different course, with the elimination of the P-bound chalcogen atom and the formation of complex **4**, which was alternatively obtained by conventional cleavage of the Ru(II) precursor with a stoichiometric amount of phosphane **1**.

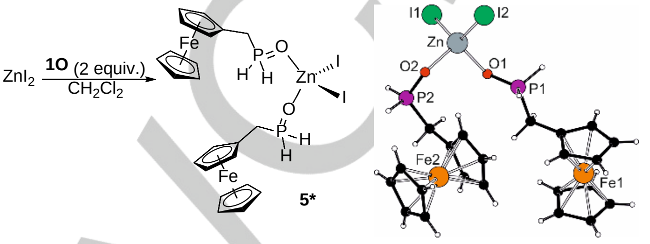


3* **4***

Scheme 2. Reactions of [(η^6-mesitylene)RuCl(μ-Cl)]$_2$ with **1E** (the asterisk indicates that the crystal structure was determined; see the Supporting Information)

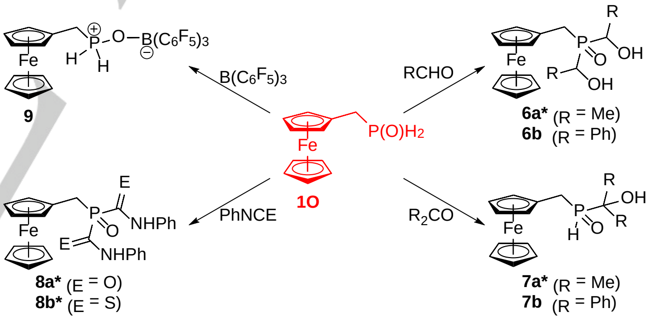
The ^{31}P NMR signatures of compounds **3** and **4** markedly differed in the magnitude of the upfield-shift and fine structure according to the substitution at the phosphorus atom [**3**: δ_P 115.0 (ddt, $^1J_{PH}$ = 110 Hz, $^2J_{PH}$ = 15 and 6 Hz), **4**: δ_P −24.0 (tt, $^1J_{PH}$ = 355 Hz, $^2J_{PH}$ = 8 Hz)]. Both complexes were unequivocally authenticated by X-ray diffraction analysis (see the Supporting Information).

In a reaction with ZnI_2, **1O** produced a phosphine oxide complex, compound **5** (Scheme 3). Although the solution NMR spectra indicated that **1O** was coordinated to Zn(II) ions, they also suggested fluxional nature of the species formed in this reaction, corresponding with the rather weak (predominantly electrostatic) interaction of the O-donor ligand **1O** with the hard Lewis acid Zn(II).



Scheme 3. Reaction of **1O** with ZnI_2 (left) and the crystal structure of complex **5** (right; for details, see the Supporting Information)

Already during the initial experiments, we noted that phosphane oxide **1O** adds across the C=O bond of the solvent when performing the oxidation of **1** by H_2O_2 in acetone. In this respect, **1O** is more reactive than its parent phosphane. This result led us to investigate addition reactions of **1O** in more detail (Scheme 4).



Scheme 4. Reactions of **1O** (asterisk indicates that the crystal structure was determined; for details, see the Supporting Information)

Thus, in a clean reaction of compound **1O** with acetaldehyde and benzaldehyde, the respective two-fold addition products **6a** and **6b**[7a] were formed as a mixture of three diastereoisomers in a statistical 1:2:1 ratio. These isomers differed in the configuration at the two stereogenic carbon centers and at the phosphorus atom (for a detailed discussion and crystal structures, see the Supporting Information). Conversely, the reaction with ketones only led to the monoaddition products **7**, even when using an excess of the carbonyl compound.[7a] Of these compounds, only **7a** resulting from **1O** and acetone could be isolated in pure form. The more sterically congested compound **7b** was in equilibrium with the starting materials,[13] which precluded its isolation by chromatography or crystallization because **1O** and Ph_2CO were partly regenerated during the purification. Lastly, in the reaction of the phosphane oxide **1O** with phenyl isocyanate[14] and isothiocyanate, the respective phosphabiurets **8a** and **8b** were formed in good yields.[15] In contrast, when treated with neat 4-ethynyltoluene (80°C/overnight), **1O** disproportionated into a mixture of **1** and **2** (*vide supra*) rather than adding to the alkyne triple bond, as expected for secondary phosphane oxides.[16]

Considering the possibility of tautomerizaton, we also investigated the interaction of **1O** with borane and tris(pentafluorophenyl)borane. Similarly to diphenylphosphane oxide,[17] when mixing **1O** with $B(C_6F_5)_3$, a bipolar Lewis pair $FcCH_2P^{(+)}(O)H_2{-}B^{(-)}(C_6F_5)_3$ (**9**) formed instead of the "conventional" Lewis adduct $FcCH_2PH(OH)\cdot B(C_6F_5)_3$. Although **9** readily decomposed and could not be crystallized, its formulation was unambiguously established from the spectroscopic data. Specifically, the signal observed in the $^{31}P\{^1H\}$ NMR spectrum of **9** was observed at a position close to that of complex **5** (δ_P 17.8) and was split into a septet by a scalar interaction with six fluorine atoms of $B(C_6F_5)_3$ in *ortho* positions. The non-decoupled ^{31}P NMR and ^1H NMR spectra confirmed the presence of two equivalent hydrogen atoms at phosphorus, whereas the position of the ^{11}B NMR resonance (δ_B 0.7) corresponded with that reported for the similar adduct resulting from $Ph_2P(O)H$.[17a] In contrast, BH_3 (1 equiv. of THF solution) addition to **1O** produced a complex mixture. ^{31}P NMR analysis allowed us to identify the parent phosphane **1** as the dominant product, in addition to unreacted **1O**, adducts **1**$\cdot BH_3$ and $FcCH_2PH(OH)\cdot BH_3$ and some unidentified minor byproducts (see the Supporting Information).

In summary, we reported the synthesis of the first bench-stable phosphane oxide. Although this compound can be conveniently synthesized, purified by chromatography and stored under ambient conditions without precautions, it retains the reactivity typical of phosphane oxides. Together with the corresponding phosphane sulfide and selenide, these compounds are the first isolable primary phosphane chalcogenides with a conventional albeit somewhat exotic "organic" substituent at the phosphorus atom.[18] With their parent compound **1**, they form a unique family of homologous compounds with a high potential for comparative studies. The first results from such studies are also presented here. Although no signs of phosphinous acid tautomer were detected in solutions of **1O**, the phosphane oxide undergoes facile tautomerization upon coordination to a soft metal ion but binds to relatively harder metal ions in its native P-oxide form. This P-oxide form also seems to be the active species in additions of **1O** to various unsaturated systems.

Acknowledgements

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Keywords: Primary phosphane chalcogenides • Phosphanes • Metallocenes • Synthesis design • Structure elucidation

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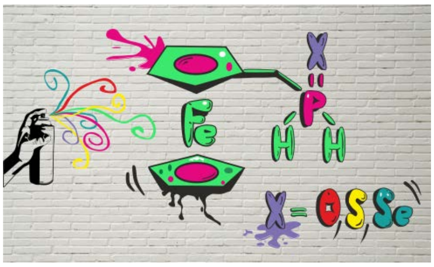

Remarkably stable (ferrocenylmethyl)phosphane oxide was synthesized as the first isolable primary phosphane oxide. Reactivity of this compound and the corresponding phosphane sulfide and selenide, which were also prepared, was studied toward diverse metal precursors and toward unsaturated organic substrates.

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