Inorganic Chemistry
Article
pubs.acs.org/IC

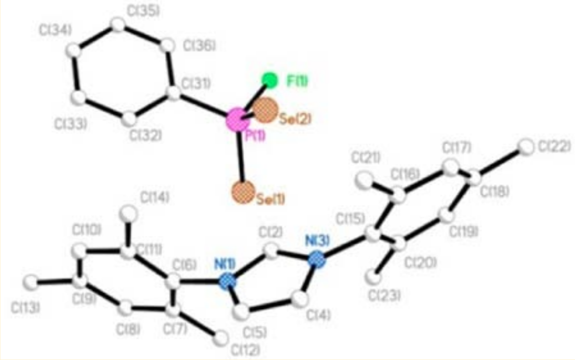
Fluorinated Phosphorus−Selenium Heteroatom Compounds: Phenylphosphonofluorodiselenoic Salts, Adducts, and Esters

Guoxiong Hua, Junyi Du, Alexandra M. Z. Slawin, and J. Derek Woollins*

EaStCHEM School of Chemistry, University of St Andrews, Fife KY16 9ST, United Kingdom

Supporting Information

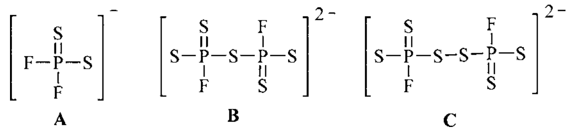
ABSTRACT: 2,4-Bis(phenyl)-1,3-diselenadiphosphetane-2,4-diselenide, $[PhP(Se)(\mu\text{-}Se)]_2$, Woollins' reagent (**WR**), reacts with dry KF or tetrabutylammonium fluoride (TBAF) at room temperature generating the corresponding potassium and tetrabutylammonium phenyldiselenofluorophosphinates **1** and **2** in almost quantitative yields. Treating **1** with equimolar amounts of tetraphenylphosphonium chloride or 1,3-dimesityl-*1H*-imidazol-3-ium chloride in THF at room temperature afforded the corresponding organic adducts **3** and **4** in 90% and 87% yields. Reaction of **1** with mono- and dihalogenated alkanes gave a series of esters of phenylphosphonofluoridodiselenoates **5**−**8** and **9** in 79−93% yields. Two representative crystal structures are reported.



INTRODUCTION

Organophosphorus−fluorine compounds (OPFCs) bearing P−F bonds have been of considerable interest since the 1970s due to their diverse chemical and biological activities. They are an important class of organophosphorus compounds and are recognized as selective phosphorylating agents in synthesis, and efficient inhibitors of several classes of enzymes.[1−12] The thiophosphate anions **A**−**C** (Scheme 1) were first prepared from the reaction of alkali metal fluorides and P_4S_{10} by Roesky and co-workers.[13,14] Since then, the synthesis of thiophosphoryl halides $S{=}PF_3$ and $S{=}PFCl_2$, and their derivatives $S{=}PF_2NH_2$, $S{=}PFClNH_2$, $S{=}PF_2N{=}PF_2X$ (X = Br, NH_2 or OH), $S{=}PF_2N{=}PCl_3$, and $S{=}PF_2N{=}PF_2N{=}C{=}NSiMe_3$, was reported.[15−20] However, there are few examples of the synthesis of simple phosphonofluorodithioates $ROP(S)(S^-)F$ containing a fluorine atom attached directly to the phosphorus atom.[15,21,22] The nucleoside phosphonofluoridodithioate monoesters were prepared *via* oxidation of nucleoside phosphonodithioate with I_2 in pyridine in the presence of TMSCl, followed by addition of triethylamine trishydrofluoride (TAF).[23,24] Similar analogues were obtained from a one-pot sequential reaction of 1,3,2-dithiaphospholane P(III) derivatives, which were converted readily into the corresponding P(V) compounds by addition of elemental sulfur and finally into phosphonofluoridodithioates by further treatment with TBAF.[25] The importance of phosphoro-fluorine compounds in pure and applied chemistry invigorated our interest in synthesizing new phosphorodiselenoates bearing the P−F motif.

Scheme 1. Fluorinated Thiophosphate Anions A−C



2,4-Bis(phenyl)-1,3-diselenadiphosphetane-2,4-diselenide $[PhP(Se)(\mu\text{-}Se)]_2$, Woollins' reagent (**WR**), has become known as a versatile selenation reagent in synthetic chemistry in recent years[26−40] because of its ease of preparation and handling.[41] As part of our investigation into the reactivity of **WR** toward inorganic or organic substrates herein, we report the synthesis of potassium and tetrabutylammonium salts of phenylphosphonofluoridodiselenoates, and the related organic adducts and esters. To the best of our knowledge this is the first reported synthesis and characterization of phenylphosphonofluorodiselenoate $[PhP(Se)(Se)F]^-$ and its structural analogues, providing a valuable addition to the library of phosphodiselenoate compounds.

RESULTS AND DISCUSSION

WR reacted with 2 equiv of fresh dry potassium fluoride at 80 °C in acetonitrile under N_2 atmosphere for 1 h giving potassium phenylphosphonofluoridodiselenoate **1** in 84% yield, or with 2 equiv of tetrabutylammonium fluoride (TBAF) at room temperature in tetrahydrofuran for 1 h to give tetrabutylammonium phenylphosphonofluoridodiselenoate **2** in 99% yield (Scheme 2). Both reactions were fast and very straightforward and must be performed in a moisture- and oxygen-free atmosphere.

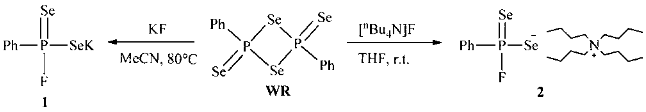
Compound **1** was obtained as a pale yellow solid and is insoluble in organic solvents but soluble in oxygen-free water.

Received: May 2, 2013
Published: July 1, 2013

ACS Publications
Published 2013 by the American Chemical Society

dx.doi.org/10.1021/ic400612w | *Inorg. Chem.* 2013, 52, 8214−8217

Scheme 2. Synthesis of Potassium and Tetrabutylammonium Salts of Phenylphosphonofluoridodiselenoate 1 and 2

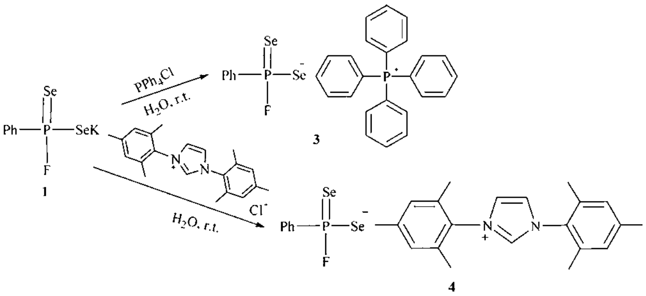


Compound **2** was obtained as brown sticky oil and is soluble in organic solvents, and shows good air stability at room temperature. **1** and **2** were fully characterized by ^{1}H, ^{13}C, ^{31}P, ^{77}Se, and ^{19}F NMR; IR spectroscopy; and mass spectrometry. Both compounds showed the anticipated molecular ion peaks $[M - K]^+$ or $[M - N^nBu_4]^+$ and satisfactory accurate mass measurement. The ^{31}P NMR spectra exhibit doublets at δ_P = 105.1 ppm in compound **1** and 102.6 ppm in compound **2**, respectively, attributed to the P−F single bond. Each signal is flanked by one set of small satellites with ^1J(P,Se) coupling constants being 728 (for compound **1**) and 770 Hz (for compound **2**); these values are considerably bigger than those in similar PSe$_2$ ions[27,42] indicating the significant electronic effect of the fluorine atom. In the ^{19}F NMR spectra, doublets are observed [^1J(P,F) coupling constants of 1073 Hz for **1** and 1068 Hz for **2**] in accord with the known literature values,[14,43] along with small ^2J(Se,F) satellites with coupling constants of 31.0 Hz for compound **1** and 31.5 Hz for compound **2**. Furthermore, the ^{77}Se NMR spectra showed double doublets at δ_{Se} = 136.3 ppm with a ^1J(P,Se) coupling constant of 728 Hz and a ^2J(Se,F) coupling constant of 31.0 Hz for compound **1**, and at δ_{Se} = 139.5 ppm with a ^1J(P,Se) coupling constant of 770 Hz and a ^2J(Se,F) coupling constant of 31.5 Hz for compound **2**. In the ^{1}H NMR spectra, compound **1** showed only phenyl protons, while in compound **2** signals for the phenyl and n-butyl groups were observed.

Treating **1** with an equimolar amount of tetraphenylphosphonium chloride in degassed water in room temperature led to the formation of tetraphenylphosphonium phenylphosphonofluoridodiselenoate **3** in 90% yield as a white solid. Similarly, reacting compound **1** with 1,3-dimesityl-*1H*-imidazol-3-ium chloride under identical conditions provided 1,3-dimesityl-*1H*-imidazol-3-ium phenylphosphonofluoridodiselenoate **4** in 87% yield as a pale pink solid (Scheme 3). Both compounds **3** and **4** are air stable and soluble in normal organic solvents. The ^{31}P, ^{77}Se, and ^{19}F NMR spectra of compounds **3** and **4** showed similar patterns to **1** with identical ^1J(P,F), ^1J(P,Se), and ^2J(Se,F) coupling constants.

Crystals of **3** and **4** suitable for X-ray analysis were obtained by diffusion of hexane into dichloromethane solutions at room temperature. X-ray structural analysis of **3** and **4** (Figures 1 and 2) reveals they crystallize as ion-separated species. The phenylphosphonofluoridodiselenoate anion contains a distorted tetrahedral phosphorus atom with P−Se bond distances [2.1136(16), 2.1163(14) Å in compound **3**, and 2.119(3), 2.108(3) Å in compound **4**] shorter than those found in amine salts of bisdiselenophosphonic acid [2.1280(11)−2.1350(12) Å];[44] however, they are still intermediate between single bond [*ca.* 2.38 Å] and double bond [P=Se double bond length *ca.* 2.08 Å],[45] indicating the delocalization of the negative charge over the FPSe$_2$ fragment.

Scheme 3. Derivatives 3 and 4 of Potassium Phenylphosphonofluoridodiselenoate 1



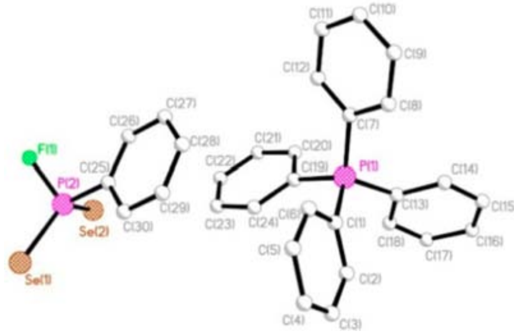


Figure 1. X-ray crystal structure of **3** (hydrogen atoms omitted for clarity). Selected bond lengths (Å) and angles (deg) (esd's in parentheses): Se(1)−P(2) 2.1136(16), Se(2)−P(2) 2.1163(14), F(1)−P(2) 1.604(3); Se(1)−P(2)−Se(2) 108.83(14), Se(1)−P(2)−F(1) 107.47(10), Se(2)−P(2)−F(1) 106.44(10).

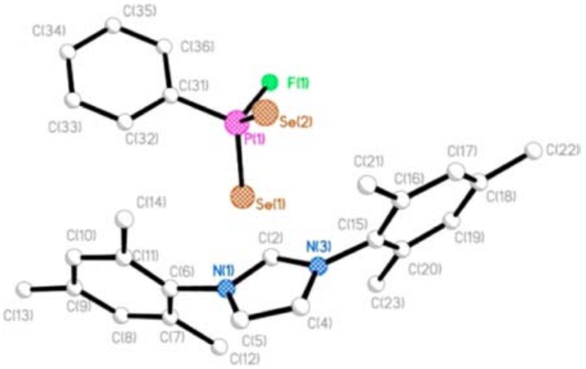
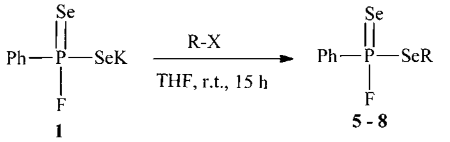


Figure 2. X-ray crystal structure of **4** (hydrogen atoms omitted for clarity). Selected bond lengths (Å) and angles (deg) (esd's in parentheses): Se(1)−P(1) 2.119(3), P(1)−F(1) 1.610(5), P(1)−Se(2) 2.108(3); Se(1)−P(1)−Se(2) 120.29(11), Se(1)−P(1)−F(1) 106.2(2), Se(2)−P(1)−F(1) 107.4(3).

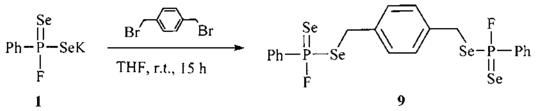
Reacting **1** with an equimolar amount of halogenated alkanes in dry THF in room temperature generates a series of esters of phenylphosphonofluoridodiselenoates **5**−**8** in 84−92% yields (Scheme 4). Furthermore, 1,4-phenylenebis(methylene) bis(phenylphosphonofluoridodiselenoate) **9** was prepared by the reaction of compound **1** with 0.5 equiv of 1,4-bis(bromomethyl)benzene under identical conditions in 79% yield as shown in Scheme 5. The esters **5**−**9** are air-stable oils or pastes and are soluble in common organic solvents such as dichloromethane, trichloromethane, acetone, and THF. Compounds **5**−**9** were fully characterized by multinuclear NMR and IR spectroscopy and accurate mass measurement. All new compounds showed the anticipated molecular ion peaks $[M]^+$, and were confirmed by satisfactory accurate mass measurements. The ^{31}P NMR spectra of esters **5**−**9** showed two

Scheme 4. Synthesis of Esters of Phenylphosphonofluoridodiselenoates 5−8



5. X = I, R = Me
6. X = I, R = 4-$NO_2C_6H_4CH_2$
7. X = I, R = 4-$BrC_6H_4CH_2$
8. X = I, R = $C_6H_5CH_2$

Scheme 5. Synthesis of 1,4-Phenylenebis(methylene) Bis(phenylphosphonofluoridodiselenoate) 9



doublets (δ_P = 102.6−103.5 ppm) with $^{31}P-^{19}F$ coupling constants (J(P,F) = 1141−1146 Hz), flanked by selenium satellites with $^{31}P-^{77}Se$ coupling constants [J(P,Se) = 481−496 and 904−909 Hz], indicating the presence of both P—Se single bond and P═Se double bond in these heteroatom compounds. In the ^{19}F NMR spectra of compounds **5**−**9**, doublets (δ_F = −58.5 to −55.8 ppm) were observed with the corresponding $^{31}P-^{19}F$ coupling constants, and each was accompanied by selenium satellites with $^{19}F-^{77}Se$ coupling constants [J(F,Se) = 17.1−19.0 and 33.3−35.4 Hz]. This was further supported by the ^{77}Se NMR spectra which showed double doublets with the respective matching $^{31}P-^{77}Se$ and $^{19}F-^{77}Se$ coupling constants. For compounds **5** and **9**, two diastereoisomers were observed in multi-NMR spectra in 2:1 and 1:4 intensity ratio, respectively.

In conclusion, Woollins' reagent reacts with dry KF or tetrabutylammonium fluoride to give the corresponding potassium and tetrabutylammonium salts of phenyldiselenofluorophosphinic acids in almost quantitative yields. Potassium phenyldiselenofluorophosphinic acid was converted readily into the corresponding organic adducts by reacting further with an equimolar amount of tetraphenylphosphonium chloride or 1,3-dimesityl-1*H*-imidazol-3-ium chloride. Furthermore, reaction of potassium phenyldiselenofluorophosphinic acid with mono- and dihalogenated alkanes afforded a series of esters of phenylphosphonofluoridodiselenoates in high yields. The structures of all new compounds have been elucidated using ^{1}H, ^{13}C, ^{31}P, ^{77}Se, and ^{19}F NMR spectroscopy and accurate mass measurement in conjunction with single crystal X-ray crystallography of two structures.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Experimental details, crystal data (CIF), and spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*Phone: (+44)-1334-463384. E-mail: jdw3@st-and.ac.uk.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We are grateful to the University of St Andrews for financial support and the EPSRC National Mass Spectrometry Service Centre (Swansea) for mass spectral measurements. We also thank Professor Andrew Smith (the University of St Andrews) for the kind supply of 1,3-dimesityl-1*H*-imidazol-3-ium chloride.

■ REFERENCES

(1) Wilson, B. W.; Walker, C. R. *Proc. Natl. Acad. Sci. U.S.A.* **1974**, *71*, 3194−3198.

(2) Bartlett, P. A.; Lamdem, L. A. *Bioorg. Chem.* **1986**, *14*, 356−377.

(3) Engel, R. *Chem. Rev.* **1977**, *77*, 349−367.

(4) Camps, F.; Coll, J.; Fabrias, G.; Guerrero, A. *Tetrahedron* **1984**, *40*, 2871−2878.

(5) Sikder, A. K.; Ghosh, A. K.; Jaiswal, D. K. *J. Pharm. Sci.* **1993**, *82*, 258−261.

(6) Marjit, D. N.; Sharma, U. S. *Indian J. Chem., Sect. A: Inorg., Bio-inorg., Phys., Theor. Anal. Chem.* **1989**, *28*, 958−961.

(7) Sikder, A. K; Pandey, K. S.; Jaiswal, D. K.; Dube, S. N.; Kumar, D.; Hussain, K.; Bhattacharya, R.; Das Gupta, S. *J. Pharm. Pharmacol.* **1992**, *44*, 1038−1040.

(8) Anderson, C.; Freeman, J.; Lucas, L. H.; Farley, M.; Dalhoumi, H.; Widlanski, T. S. *Biochemistry* **1997**, *36*, 2586−2594.

(9) Ashani, Y.; Leader, H.; Rothschild, N.; Dosoretz, C. *Biochem. Pharmacol.* **1998**, *55*, 159−168.

(10) Bollmark, M.; Stawinski, J. *Nucleosides Nucleotides* **1998**, *17*, 663−680.

(11) Eyer, P. *Toxicol. Rev.* **2003**, *22*, 165−190.

(12) Kim, T. H.; Oh, K. A.; Park, N. J.; Park, N. S.; Kim, Y. J.; Yum, E. K.; Jung, Y. S. *J. Appl. Biomed.* **2006**, 67−72.

(13) Roesky, H. W.; Tebbe, F. N.; Muetterties, E. L. *J. Am. Chem. Soc.* **1967**, *89*, 1272−1274.

(14) Roesky, H. W.; Tebbe, F. N.; Muetterties, E. L. *Inorg. Chem.* **1970**, *9*, 831−836.

(15) Roesky, H. W. *Chem. Ber.* **1968**, *101*, 3679−3687.

(16) Roesky, H. W.; Beyer, H. *Chem. Ber.* **1969**, *102*, 2588−2594.

(17) Roesky, H. W.; Grimm, L. F. *Chem. Ber.* **1969**, *102*, 2319−2329.

(18) Roesky, H. W.; Grimm, L. F. *Chem. Ber.* **1970**, *103*, 1664−1673.

(19) Roesky, H. W.; Grimm, L. F. *Angew. Chem.* **1970**, *82*, 255−256.

(20) Roesky, H. W.; Grimm, L. F. *Angew. Chem., Int. Ed.* **1970**, *9*, 244−245.

(21) Harris, R. K. *J. Chem. Soc., Dalton Trans.* **1972**, 1590−1596.

(22) Fluck, E.; Schmidt, R.; Haubold, W. *Phosphorus Sulfur* **1978**, *5*, 141−146.

(23) Stawinski, J.; Bollmark, M. *Tetrahedron Lett.* **1996**, *37*, 5739−5742.

(24) Dabkowski, W.; Michalska, M.; Tworowska, I. *Chem. Commun.* **1998**, 427−428.

(25) Tworowska, I.; Dabkowski, W. *Chem. Commun.* **1998**, 2611−2612.

(26) For reviews see: (a) Hua, G.; Woollins, J. D. *Angew. Chem., Int. Ed.* **2009**, *48*, 1368−1377. (b) Woollins, J. D. *Synlett* **2012**, *23*, 1154−1169.

(27) Hua, G.; Zhang, Q.; Li, Y.; Slawin, A. M. Z.; Woollins, J. D. *Tetrahedron* **2009**, *65*, 6074−6082.

(28) Hua, G.; Li, Y.; Fuller, A. L.; Slawin, A. M. Z.; Woollins, J. D. *Eur. J. Org. Chem.* **2009**, 1612−1618.

(29) Gomez, C. J. A.; Romano, R. M.; Beckers, H.; Willner, H.; Della, V. C. O. *Inorg. Chem.* **2010**, *49*, 9972−9979.

(30) Hua, G.; Fuller, A. L.; Li, Y.; Slawin, A. M. Z.; Woollins, J. D. *New J. Chem.* **2010**, *34*, 1565−1571.

(31) Abdo, M.; Zhang, Y.; Schramm, V. L. *Org. Lett.* **2010**, *12*, 2982−2985.

(32) Huang, Y.; Jahreis, G.; Luecke, C.; Wildemann, D.; Fischer, G. *J. Am. Chem. Soc.* **2010**, *132*, 7578−7579.

(33) Hua, G.; Fuller, A. L.; Slawin, A. M. Z.; Woollins, J. D. *Eur. J. Org. Chem.* **2010**, 2607−2615.

(34) Hua, G.; Henry, J. B.; Li, Y.; Mount, A. R.; Slawin, A. M. Z.; Woollins, J. D. *Org. Biomol. Chem.* **2010**, *8*, 1655−1660.

(35) Hua, G.; Fuller, A. L.; Slawin, A. M. Z.; Woollins, J. D. *Polyhedron* **2011**, *30*, 805−808.

(36) Hua, G.; Fuller, A. L.; Slawin, A. M. Z.; Woollins, J. D. *Eur. J. Org. Chem.* **2011**, 3067−3073.

(37) Hua, G.; Cordes, D. B.; Li, Y.; Slawin, A. M. Z.; Woollins, J. D. *Tetrahedron Lett.* **2011**, *52*, 3311−3314.

(38) Wong, R. C. S.; Ooi, M. L. *Inorg. Chim. Acta* **2011**, *366*, 350−356.

(39) Hua, G.; Griffin, J. M.; Ashbrook, S. E.; Slawin, A. M. Z.; Woollins, J. D. *Angew. Chem., Int. Ed.* **2011**, *50*, 4123−4326.

(40) (a) Hua, G.; Fuller, A. L.; Slawin, A. M. Z.; Woollins, J. D. *Synlett* **2012**, *23*, 2453−2458. (b) Hua, G.; Slawin, A. M. Z.; Woollins, J. D. *Synlett* **2012**, *23*, 1170−1174. (c) Hua, G.; Woollins, J. D. *Polyhedron* **2012**, *42*, 190−195.

(41) Gray, I. P.; Bhattacharyya, P.; Slawin, A. M. Z.; Woollins, J. D. *Chem.—Eur. J.* **2005**, *11*, 6221−6227.

(42) Gray, I. P.; Slawin, A. M. Z.; Woollins, J. D. *Dalton Trans.* **2005**, 2188−2194.

(43) Roesky, H. W. *Z. Naturforsch.* **1967**, *22b*, 716−718.

(44) Hua, G.; Li, Y.; Slawin, A. M. Z.; Woollins, J. D. *Tetrahedron* **2008**, *64*, 5442−5448.

(45) Nguyen, C. Q.; Adeogun, A.; Afzaal, M.; Malik, M. A.; O'Brien, P. *Chem. Commun.* **2006**, 2179−2181.