Keaction of Vinyl Selenides with Secondary Phosphines and Elemental Selenium: One-Pot Selective Synthesis of a New Family of Diselenophosphinic *Se*-Esters

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ABSTRACT: Alkyl vinyl selenides react with diverse secondary phosphines and elemental selenium in a 1.1:1:2 molar ratio (120-124°C, 20-40 min, 1,4dioxane) to afford selectively earlier unknown diselenophosphinic Se-esters, $R_2P(Se)SeCH(Me)SeR'$, in 82-99% yield. This three-component atom-economic reaction proceeds via intermediate formation of diselenophosphinic acid $R_2P(Se)SeH$ (generated from secondary phosphine and selenium), which adds to the double bond of vinyl selenide in a Markovnikov manner to give the target products. © 2014 Wiley Periodicals, Inc. Heteroatom Chem. 00:1–5, 2014; View this article online at wileyonlinelibrary.com. DOI 10.1002/hc.21144

INTRODUCTION

S-Esters of dithiophosphinic acids, $R_2P(S)SR'$ (R, R' = organic groups), represent a well-known and exhaustively investigated family of chalcogenophosphorus compounds [1]. At the same time, their selenium analogues, i.e., diselenophosphinic *Se*-esters, are poorly studied, although they are of great theoretical and practical interest in light of the high biological activity of selenium compounds [2]. Furthermore, recently it has been shown that the diselenophosphinic *Se*-esters are iniferter agents for living free radical polymerization of styrene [3]. Among related compounds, diselenophosphonic *Se*-esters are successfully employed for hydroselenophosphorylation of alkenes leading to optically active selenophosphonic *O*,*O*'-esters [4].

As for the synthesis of diselenophosphinic *Se*esters [5] and their -phosphate [6] or -phosphonate congeners [7], the most conventional method is the reaction between organic halides and the salts of $[R_2PSe_2]Cat$ type (R = organic groups, RO or R_2N ; Cat = metal or ammonium). Alternatively, such *Se*-esters can be assembled by condensation of selenophosphinic chlorides, $R_2P(Se)Cl$, with metal alkyl- or arylselenolates [3]. Meanwhile, these approaches do not always lead to functional

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R ¹ Se	+ $H = P(R^2 + R^2)$	2Se	120–124°C, 20–40	min Se	Se Se Se	
			1,4-Dioxane	→ P R ^{2′} F	∣ R' ≀² Me	
1, 2 Entry	3–6 Vinylselenide		Phosphine	Product	7a–h Isolate Yield	
1	<i>n</i> -C ₅ H ₁₁ ∖Se (1)		(3)	7a	97	
2	<i>n</i> -C ₆ H ₁₃ ∖Se (2)		(3)	7b	99	
3	<i>n-</i> C₅H ₁₁ Se (1)		р-н (4)	7с	98	
4	<i>n-</i> C ₆ H ₁₃ Se (2)			7d	96	
5	<i>n</i> -C ₅ H ₁₁ ∖Se (1)			7e	82	
6	<i>n</i> -C ₆ H ₁₃ Se (2)		cr/ p−−− (5)	7f	99	
7	<i>n</i> -C ₅ H ₁₁ ∖Se (1)		, с с с с с с с с с с с с с с с с с с с	7g	98	
8	<i>n-</i> C ₆ H ₁₃ ∖Se (2)		, _o, , , , , , , , , , , , , , , , , ,	7h	94	

TABLE 1 One-Pot Synthesis of Diselenophosphinic Se-Esters 7a-h^a

^aThe reaction conditions: vinyl selenide (1.1 mmol), secondary phosphine (1.0 mmol), selenium (2.0 mmol), and 1,4-dioxane at 120–124°C for 20–40 min.

diselenophosphinic *Se*-esters, which are most interesting for subsequent applications. From the point of view of synthetic efficacy and atomic economy, direct addition of diselenophosphinic acids, $R_2P(Se)SeH$, to the C=C or C=C bonds of unsaturated compounds would be the ideal route to functional diselenophosphinic *Se*-esters. However, this

prospective pathway is particularly challenging because the free diselenophosphinic acids, in contrast to dithiophosphinic acids [1], are very unstable and instantly decompose [8]. More recently, we have designed a convenient method for in situ generation of diselenophosphinic acids (from secondary phosphines and elemental selenium), which immediately add to electron-rich alkenes in a reaction mixture. In this manner, novel functional *Se*-esters of diselenophosphinic acids have been prepared by using various alkenes, e.g., styrenes [9], vinyl ethers [10], and vinyl sulfides [11].

Herein, we reported the synthesis of a new family of diselenophosphinic *Se*-esters containing alkylselanyl groups, $R_2P(Se)SeCH(Me)SeR'$, based on a selective atom-economic reaction between vinyl selenides, secondary phosphines, and elemental selenium.

RESULTS AND DISCUSSION

We have found that the alkyl vinyl selenides **1**, **2** interact easily with secondary phosphines **3–6** and elemental selenium in a three-component type reaction at $120-124^{\circ}C$ (1,4-dioxane, 20-40 min) to afford selectively hitherto unknown diselenophosphinic *Se*esters **7a–h** in high to quantitative yields (Table 1). The molar ratio of the reactants is close to stoichiometric (vinyl selenide/phosphine/Se = 1.1:1:2); however, the small excess (10 mol%) of vinyl selenide is required to achieve the highest yields of products **7a–h**. Notably, the order of reactants mixing does not affect the reaction course and the products' yields. As seen from Table 1, the reaction studied appears to be of general character for secondary phosphines bearing diverse organic groups.

At a lower temperature (80-100°C), the reaction proceeds either too slow or does not occur at all (at a temperature <80°C). For example, vinyl selenide 1 reacts with secondary phosphine 3 and elemental selenium at 100°C for 1.5 h to afford Se-esters 7a in low yield (~20%) along with bis(2-phenethyl)phosphine selenide (8); some unreacted selenium being recovered. Noteworthy, a similar three-component reaction involving alkyl vinyl sulfides takes place under comparable conditions (100°C, 1.5 h) to quantitatively give Se-[1]-(alkylsulfanyl)ethyl]diselenophosphinates [11]. The same reaction with alkyl vinyl ethers is realized even easily (90°C, 1-1.5 h), resulting in Se-[1-(alkoxy)ethyl]diselenophosphinates in up to 99% yield [10]. The observed order of the chalcogenides reactivity in the addition studied (AlkOCH= CH_2 > $AlkSCH=CH_2 > AlkSeCH=CH_2$) corresponds to the expected drop of the stabilization effect in the intermediate carbocation by the adjacent chalcogenide, which once more supports the electrophilic nature of the reaction.

It has been found that the secondary phosphine selenides may be alternatively used in the threecomponent reaction instead of secondary phosphines. For instance, vinyl selenides **1**, **2** react with bis(2-phenethyl)phosphine selenide (**8**) and elemental selenium in a 1.1:1:1 molar ratio under the same conditions (120–124°C, 20–40 min, 1,4-dioxane) to furnish *Se*-esters **7a,b** in excellent yield (Scheme 1).

At the same time, divinyl selenide reacts with secondary phosphines and elemental selenium under similar conditions (120–124°C, 40 min, at 1:1:2 or 1:2:4 molar ratios) to furnish a mixture of eight phosphorus-containing compounds, in which monoand diadducts of diselenophosphinic acids to divinyl selenide prevail (¹H, ³¹P NMR data).

The compounds 7a-h are stable in air and moisture for several months. Their structures were established by ¹H, ¹³C, ³¹P, and ⁷⁷Se NMR as well as IR spectroscopy. So, the ³¹P NMR spectra of **7a-h** reveal sharp singlets at 49.05-51.85 ppm, flanked by two pairs of ⁷⁷Se satellites with ${}^{1}J_{P-Se}$ coupling constants in the range of 359-368 and 740-750 Hz, indicating the presence of P—Se single bonds and P=Se double bonds in each compound. Accordingly, the ⁷⁷Se NMR spectra of **7a-h** display signals originating from the P—Se and P=Se bonds in the region of δ = 352–354 and –248 to –245 ppm, respectively, with matching ${}^{1}J_{P-Se}$ coupling constants. The alkylselenyl moieties in the ⁷⁷Se NMR spectra appear as low-field singlets at 326–329 ppm. ¹H and ¹³C NMR spectra of compounds 7a-h display characteristic peaks corresponding to the organic groups.

A plausible mechanism of the *Se*-esters **7a-h** formation is shown in Scheme 2. The first stage is well-known [12] oxidation of secondary phosphine **3–6** with elemental selenium to give the secondary phosphine selenide **A**. At the second stage, phosphine selenide **A** is further oxidized with selenium to generate diselenophosphinic acid **B**, which finally adds to the double bond of vinyl selenide to afford ester **7**. The last stage proceeds strictly as the Markovnikov addition, since the alternative products (anti-Markovnikov adducts) have not been detected in the reaction mixtures (¹H, ³¹P NMR). Therefore, the reaction is the first example of electrophilic addition of diselenophosphinic acids to vinyl selenides.

The proposed mechanism is supported by the following evidence: when vinyl selenides 1, 2 are used in a deficient amount (i.e., at the molar ratio 1, 2/3-6 < 1), we observed that selenoanhydrides, $(R_2P = Se)_2Se$, formed as by-products together with *Se*-esters 7a–h. Obviously, the formation of the selenoanhydrides is due to the decomposition of the intermediate diselenophosphinic acids, $R_2P(Se)SeH$ (Scheme 2). One of such selenoanhydrides, where $R = CH_2CH_2Ph$ (9), has been isolated from the reaction mixture, and its structure was established by X-ray (Fig. 1).







SCHEME 2 A pathway of the three-component reaction.



FIGURE 1 ORTEP diagram of the molecular structure of selenoanhydride 9 (30% thermal ellipsoid probability). Selected bond distances (Å) and angles (°): P(1)-Se(1) 2.1025(10), P(1)-Se(3) 2.2538(10), P(2)-Se(2) 2.0892(9), P(2)-Se(3) 2.2775(9), Se(1)-P(1)-Se(3) 103.35(4), Se(2)-P(2)-Se(3) 117.14(4), P(1)-Se(3)-P(2) 109.01(3).

CONCLUSIONS

In summary, examples of diselenophosphinic *Se*esters with alkylselanyl moieties have been synthesized via the selective atom-economic reaction between vinyl selenides, secondary phosphines, and elemental selenium. This reaction involves tandem formation of unstable diselenophosphinic acids, which immediately add to vinyl selenides to form Markovnikov adducts, i.e., diselenophosphinic *Se*esters. The latter are prospective reversible addition fragmentation chain transfer agents for living polymerization of vinyl monomers as well as promising sources of selenium for fabrication of metal selenide nanocrystals. Also, availability of the three unequal selenium atoms in esters **7a–h** makes their potential *Se,Se',Se*"-donating ligands for the assembly of novel selenium-rich metal complexes.

EXPERIMENTAL

General

All reactions were performed under inert atmosphere (dry argon), using an enclosed glass tube or a round-bottomed flask equipped with a condenser, a thermometer, and an argon inlet. 1,4-Dioxane was distilled from sodium/benzophenone under inert atmosphere prior to use. Vinyl selenides 1, 2 were prepared according to the literature method [13]. Secondary phosphines **3–6** were synthesized by hydrophosphination of styrene, 4-chlorostyrene, 4-tert-butylstyrene, or 4-tert-butoxystyrene, respectively [14]. Powdered gray selenium was used as purchased. Phosphine selenide 8 was obtained by oxidation of phosphine **3** with selenium [[12]b]. The elemental analyses were performed using a Flash EA 1112 Series CHNS analyzer. The ¹H, ¹³C, ³¹P, and ⁷⁷Se NMR spectra were recorded using a Bruker AV-400 spectrometer (400.13, 100.62, 161.98, and 76.31 MHz, respectively). 85% H₃PO₄/H₂O was employed as an external standard for ³¹P NMR, HMDS was used for ¹H and ¹³C NMR, and Me₂Se was the external standard for ⁷⁷Se NMR.

General Procedure for the Synthesis of Diselenophosphinic Se-Esters **7a–h** (*Table 1*)

Powdered gray selenium (1.0 mmol, 79 mg) was added to a solution of vinyl selenide 1, 2

(0.55 mmol) and secondary phosphine **3–6** (0.5 mmol) in 1,4-dioxane (4 mL) at ambient temperature. The suspension was stirred at 120–124°C until the dissolution of selenium precipitate (20–40 min) to give a yellowish transparent solution. The solvent and excess of vinyl selenide were removed under reduced pressure (1 Torr, 50–60°C), and the residue was purified by flash-chromatography (3 cm of silica gel, hexane-ether 1:1 as an eluent) to give diselenophosphinic *Se*-ester **7a–h**.

Synthesis of Esters **7a**,**b** from Secondary Phosphine Selenide **8** (Scheme 1)

Powdered gray selenium (0.5 mmol, 40 mg) was added to a solution of vinyl selenide **1**, **2** (0.55 mmol) and bis(2-phenethyl)phosphine selenide (**8**) (0.5 mmol, 161 mg) in 1,4-dioxane (4 mL) at ambient temperature. The suspension was stirred at 120–124°C for 40 min to give a yellowish transparent solution. The solvent and excess of vinyl selenide were removed under reduced pressure (1 Torr, 50–60°C), and the residue was purified by flash-chromatography (3 cm of silica gel, hexane–ether 1:1 as the eluent) to give diselenophosphinic *Se*-esters **7a,b** in 95% and 86% yield, respectively.

X-Ray Crystallography of 9

A single crystal of **9** was mounted on glass fibers with epoxy resin, and all geometric and intensity data were collected using a Bruker APEXII CCD diffractometer using graphite-monochromated Mo-K α radiation ($\lambda = 0.71073$ Å). Data reduction was carried out with *SAINT-Plus* software [15]. An empirical absorption correction was applied using the *SADABS* program [16]. The structure was solved by direct methods and refined by full-matrix least squares on F^2 using the *SHELXTL* software package [17], incorporated in *SHELXTL/PC* version 5.10.28 [18].

Crystal data for **9**: $C_{32}H_{36}P_2Se_3$, M = 719.43, monoclinic, space group $P2_1/c$, a = 14.5059(8), b = 10.1924(6), c = 23.5251(13), $\beta = 107.6690(10)$, V = 3314.1(3) Å, Z = 4, $\rho_{calcd.} = 1.442$ g/cm⁻³, $\mu = 3.445$, T = 296(2) K. Reflections collected/unique = 42,388/6810 [*R*(int) = 0.0545], final *R* indicates [$I > 2\sigma(I)$], $R_1 = 0.0381$, w $R_2 = 0.0889$. CCDC 968547 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/ data_request/cif.

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