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Syntheses and Fluoride-Ion-Mediated Hydrolysis of Phosphoroselenoic Acid Ester and Amides

Toshiaki Murai, Shinsuke Inaji, and Tohru Takenaka

Department of Chemistry, Faculty of Engineering, Gifu University, Yanagido, Gifu 501-1193, Japan

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ABSTRACT: *Phosphoroselenoic acid ester and amides containing binaphthoxy moiety were prepared by reacting phosphoroselenoyl chloride with alcohols and secondary amines. The resulting amides underwent fluoride-ion-mediated hydrolysis with a THF solution of tetrabutylammonium fluoride to give two types of phosphoroselenoic acid ammonium salts: one with a fluorine atom and another with a binaphthoxy group on the phosphorus atom. The ratio of these products depended on the substituents on the nitrogen atom of the amides. A similar reaction of the ester with tetrabutylammonium fluoride gave two types of ammonium salts. The formation of these products was confirmed by converting them to the corresponding methyl esters.* © 2009 Wiley Periodicals, Inc. Heteroatom Chem 20:255–261, 2009; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/hc.20544

INTRODUCTION

The high affinity of the fluorine atom toward the phosphorus atom has been used as a driving force to promote the substitution reaction at the phosphorus atom. In the reaction of pentavalent phosphorus compounds, chlorine atom and oxygen-containing substituents have usually been used as leaving groups [1–6]. A variety of pentavalent phosphorus compounds bearing a phosphorus–fluorine bond, many of which are of interest from the perspective of biological activity [7–11], have been prepared by these methods. In this regard, we identified the fluoride-ion-mediated hydrolysis of phosphoric acid esters and amides leading to phosphorofluoridic and phosphoramidofluoridic acid salt monoesters as products [12] (Scheme 1), during our studies on the synthesis and properties of compounds with P=Se bonds [13–22]. Then, we turned back our attention to the reaction mode of phosphoroselenoic acid esters and amides. As readily available *O*,*O*-diaryl *O*-alkyl phosphoroselenoic acid esters and amides, those containing binaphthoxy moiety were chosen. We herein report their fluorine-mediated hydrolysis.

RESULTS AND DISCUSSION

Initially, the starting phosphoroselenoic acid ester and amides were synthesized (Scheme 2). The chloride **1**, which was readily prepared from PCl_3, Se, and 1,1′-bi-2-naphthol, was stirred with **2** in the presence of Et_3N (2 equiv) for 3.5 h under reflux in THF to give the desired ester **3** quantitatively [19]. Likewise, the reaction of **1** with amines **4** proceeded smoothly to give the corresponding amides **5** in high yields, but the reaction time and the use of extra amines depended on the substituents in amines **4**. In the synthesis of amides **5a** and **5d**, amines **4a** and **4d** (2 equiv) were used, and the reaction was completed within 2 h under reflux in toluene, whereas

Correspondence to: Toshiaki Murai; e-mail: mtoshi@gifu-u.ac.jp.

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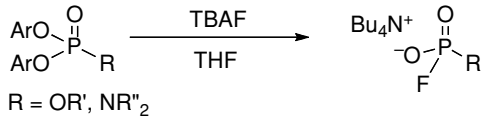
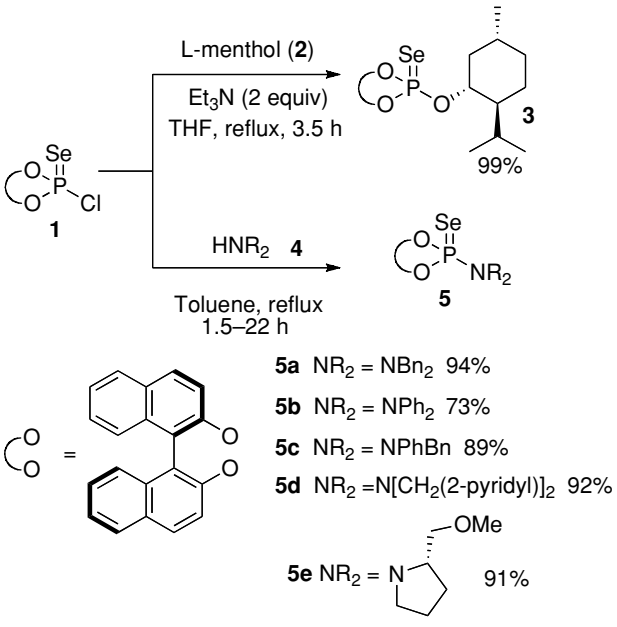


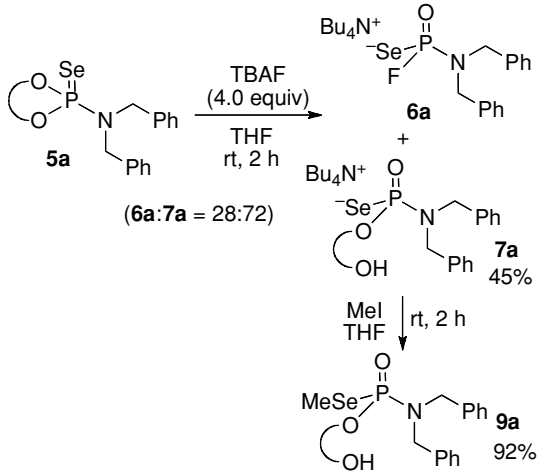
SCHEME 1

the reaction with amine **4c** required a longer reaction time. For the reaction with diphenylamine (**4b**), DMAP was necessary to complete the reaction. Similarly to reduce the amount of amine **4e**, DMAP was used as an additive.

Second, fluoride-ion-mediated hydrolysis of phosphoroselenoic amides was carried out (Scheme 3). Phosphoroselenoic amide **5a** was reacted with a THF solution of tetrabutylammonium fluoride (TBAF) at room temperature. The starting material **5a** disappeared within 2 h. In the ^{31}P NMR spectra of the crude products, two types of signals were observed at 54.0 and 55.1 ppm with satellite signals due to coupling with ^{77}Se atom. One of them was observed as a doublet signal due to coupling with ^{19}F atom ($J^{1}_{P\text{-}F}$ = 1083 Hz). Based on these spectra and those of the products described later, the two products were identified as salts **6a** and **7a**, and they were formed in a ratio of 28:72. These products could be purified by column chromatography on silica gel. In this case, the product **7a** was isolated in 45% yield as a stable compound. To further confirm the formation of **7a**, it was methylated with MeI in THF. This methylation



SCHEME 2

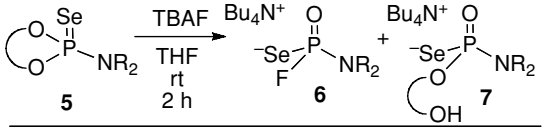


SCHEME 3

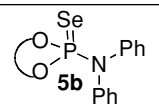
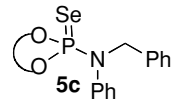
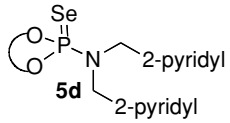
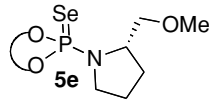
took place selectively at the selenium atom of **7a** to give phosphoramidoselenoic acid *Se*-ester **9a** in high yield. This fluoride-ion-mediated hydrolysis was then applied to a variety of amides **5b**–**5e** (Table 1). In all cases, a mixture of salts containing a fluorine atom **6** and salts with a binaphthoxy group **7** was formed, and their ratio was affected by the substituents on the amino groups. Products **6** are rare examples of phosphorus(V) compounds that possess fluorine and selenium atoms [23,24]. The use of *N*,*N*-diphenyl amide **5b** gave mainly the salt **6b** (entry 1), which was successfully methylated with MeI to give *Se*-methyl ester **8b**. In contrast, the reaction of **5c** with a THF solution of TBAF gave two salts **6c** and **7c** in a nearly equal ratio (entry 2). Both salts were isolated as major products, although they could not be completely separated. Nevertheless, methylation of the mixture of **6c** and **7c** followed by purification by column chromatography led to pure esters **8c** and **9c**. For the reaction of amides **5d** and **5e**, the salts **7** were formed as major products (entries 3 and 4), and methylation led to *Se*-methyl esters **9d** and **9e**.

A plausible reaction pathway for the present reaction is shown in Scheme 4. Initially, the substitution reaction at the phosphorus atom in **5** with F^- in TBAF may take place with cleavage of one of the binaphthyloxy-phosphorus bonds to give the salts **10**, followed by protonation with H_2O in a THF solution of TBAF, to give intermediates **11**. Hydroxide ion (OH^-) then nucleophilically attacks the phosphorus atom in **11**. Cleavage of the other binaphthyloxy-phosphorus bond (path A) may lead to **6** via **12**. In contrast, fluorine atom acts as a leaving group in the substitution reaction with OH^- (path B) to give the

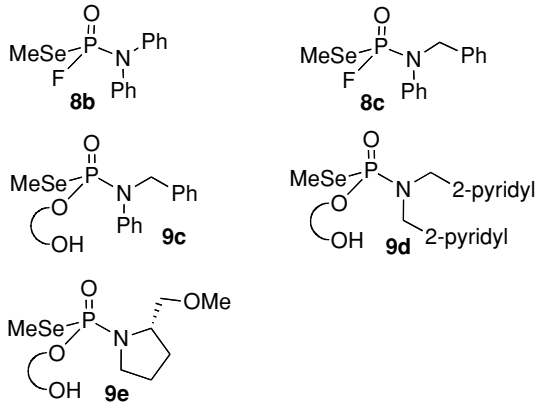
TABLE 1 Fluoride-Ion Mediated Hydrolysis of Phosphoroselenoic Amides **5**



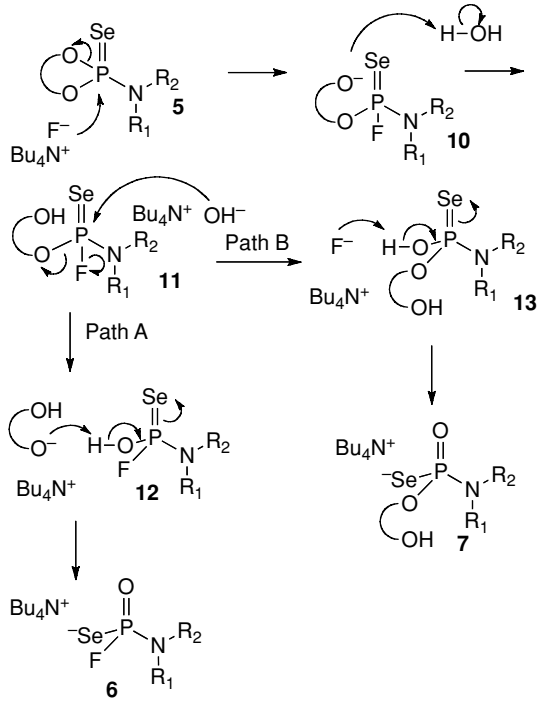
5 **6** **7**

Entry	5	Ratio of 6 and 7 in Crude Products	Isolated Yield
1	 **5b**	87:13	**6b** 100%[a]
2	 **5c**	60:40	**6c** + **7c** (86:14) 51% **6c** + **7c** (23:77) 27%
3	 **5d**	34:64	**7d** 64%
4	 **5e**	22:78	**7e** 72%

[a]Yield of the crude product **6** contaminated with unreacted TBAF.

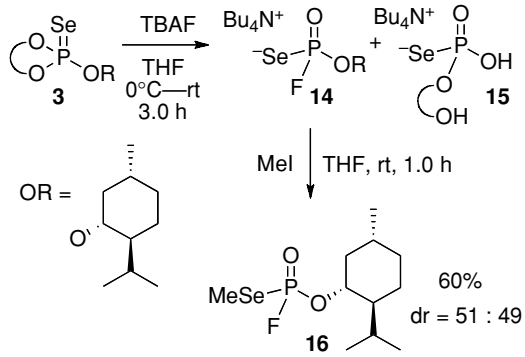


8b **8c** **9c** **9d** **9e**



5 **10** **11** **12** **13** **6** **7**

SCHEME 4



3 **14** **15** **16**

SCHEME 5

salts **7** via **13**. While the factors that control the selectivity for path A or B are currently unclear, the Lewis basicity of the amino groups in **11** may play an important role since the amides **5b** and **5c**, in which the phenyl group is attached to the nitrogen atom, are predominantly converted to salts **6**.

Finally, ester **3** was treated with TBAF in THF (Scheme 5). The reaction went to completion within 3 h, and two types of signals were observed at 41.3 and 45.1 ppm, analogous to those in the reaction of amides **5**. Therefore, the products were tentatively considered to be fluoridate **14** and acid salt **15**, which were formed in a ratio of 60:40. These products may be diastereomeric mixtures but could not be distinguished in ^{31}P NMR spectra. To confirm the diastereomeric ratio of **14**, methylation of **14** with MeI was carried out. As a result, two diastereomers of **16** were formed in a nearly equal ratio.

CONCLUSION

We have demonstrated the synthesis and fluoride-ion-mediated hydrolysis of phosphoroselenoic acid ester and amides with a 1,1′-bi-2-naphthyl group. These syntheses were achieved by reacting phosphoroselenoyl chloride with alcohol or amines in the presence or absence of extra amines as an additive. The reaction of ester with a THF solution of

TBAF was complete within 3 h to give phosphorofluoridoselenoic acid salt and phosphoroselenoic acid salt. A similar reaction with amides gave phosphoramidofluoridoselenoic acid salts and phosphoramidoselenoic acid salts, and the ratio of these salts depended on the substituents on the amino groups. The methylation of the resulting salts with MeI proceeded smoothly at the selenium atom to give *Se*-methyl esters.

EXPERIMENTAL

Typical Procedure for the Synthesis of Amides

*A Method Using Excess Amines: Synthesis of (R_{ax})-N,N-Dibenzyl-dinaphtho[2,1-d:1′,2′-f][1,3,2]-dioxaphosphepine-4-amine-4-selenide (***5a***).* To a toluene solution (10 mL) of the chloride (R_{ax})-**1a** (2.15 g, 5.0 mmol) was added dibenzylamine (1.92 mL, 10 mmol) at room temperature under an Ar atmosphere. The resulting solution was stirred at reflux in toluene for 2 h and concentrated in vacuo. The reaction mixture was purified by column chromatography on silica gel (hexane:CH_2Cl_2 = 1:1, Rf = 0.55) to give the corresponding selenide **5a** (2.76 g, 94%) as a colorless solid. mp: 216–218°C; IR (KBr): 3455, 3025, 2921, 2792, 2596, 1588, 1495, 1455, 1360, 1321, 1221, 1201, 1157, 1108, 1065, 1028, 978, 943, 913, 859, 833, 808, 785, 745, 693, 651, 624, 590, 563, 513, 485, 452 cm^{-1}; ^1H NMR ($CDCl_3$) δ: 3.62 (dd, J = 11.3 Hz, 15.4 Hz, 2H, NCH_2), 4.64 (dd, J = 11.2 Hz, 15.1 Hz, 2H, NCH_2), 6.87–8.10 (m, 22H, Ar); ^{13}C NMR ($CDCl_3$) δ: 50.2 (NCH_2), 50.3 (NCH_2), 120.5, 122.0, 122.1, 122.3, 125.7, 126.5, 126.7, 127.1, 127.2, 127.9, 128.3, 128.6, 128.8, 130.9, 131.3, 132.0, 132.3, 132.4, 147.0, 147.0, 148.9 149.0 (Ar); ^{31}P NMR ($CDCl_3$) δ: 88.4 ($^1J_{P\text{-}Se}$ = 975.7 Hz); ^{77}Se NMR ($CDCl_3$) δ: −304.1 ($^1J_{Se\text{-}P}$ = 975.7 Hz); MS (EI) m/z: 590 (M^+); Anal. Calcd for $C_{34}H_{26}NO_2PSe$: C, 69.16; H, 4.44; N, 2.37. Found: C, 69.22; H, 4.65; N, 2.53.

*A Method Using DMAP: Synthesis of (R_{ax})-N,N-Diphenyl-dinaphtho[2,1-d:1′,2′-f][1,3,2]dioxaphosphepin-4-amine-4-selenide (***5b***).* To a dry toluene solution (5 mL) of the chloride (R_{ax})-**1a** (1.08 g, 2.5 mmol) and DMAP (366 mg, 3.0 mmol) was added diphenylamine (510 mg, 3.0 mmol) at room temperature under an Ar atmosphere. The resulting solution was stirred at reflux in toluene for 22 h and concentrated in vacuo. The reaction mixture was purified by column chromatography on silica gel (hexane:CH_2Cl_2 = 1:1, Rf = 0.53) to give the corresponding selenide **5b** (1.02 mg, 73%) as a colorless solid.

mp: 272–284°C; IR (KBr): 3063, 1590, 1487, 1318, 1222, 1200, 1069, 1037, 952, 887, 839, 813, 755, 699, 629, 577, 563, 476 cm^{-1}; ^1H NMR ($CDCl_3$) δ: 5.19–7.94 (m, 22H, Ar); ^{13}C NMR ($CDCl_3$) δ: 120.5, 121.9, 122.0, 122.5, 125.6, 126.3, 126.5, 127.0, 127.2, 127.6, 128.2, 128.6, 129.0, 130.3, 130.8, 131.3, 132.0, 132.3, 132.5, 143.1, 146.3, 146.4, 148.8, 148.9 (Ar); ^{31}P NMR ($CDCl_3$) δ: 76.7 ($^1J_{P\text{-}Se}$ = 989 Hz); ^{77}Se NMR ($CDCl_3$) δ: −215.6 (d, $^1J_{Se\text{-}P}$ = 989 Hz); MS (EI) m/z: 563 (M^+); HRMS Calcd for $C_{32}H_{22}NO_2PSe$: 563.0553. Found: 563.0544.

*(R_{ax})-N-Phenyl-N-phenylmethyl-dinaphtho[2,1-d:1′,2′-f][1,3,2]dioxaphosphepine-4-amine-4-selenide (***5c***).* mp: 88–93°C; IR (KBr): 3435, 3059, 1734, 1591, 1507, 1492, 1462, 1433, 1361, 1323, 1223, 1155, 1096, 1065, 1029, 980, 953, 915, 855, 836, 813, 772, 750, 720, 695, 652, 625, 599, 565, 549, 522 cm^{-1}; ^1H NMR ($CDCl_3$) δ: 4.68dd, $^2J_{H\text{-}H}$ = 14.8 Hz, $^3J_{H\text{-}P}$ = 11.2, 1H, CH_2Ph), 4.78dd, $^2J_{H\text{-}H}$ = 14.8 Hz, $^3J_{H\text{-}P}$ = 11.2, 1H, CH_2Ph), 7.02–8.07 (m, 22H, Ar); ^{13}C NMR ($CDCl_3$) δ: 57.8 (d, $^2J_{C\text{-}P}$ = 5.8 Hz, CH_2Ph), 120.7, 121.5, 122.1, 122.4, 125.6, 125.6, 126.5, 126.5, 127.0, 127.2, 127.6, 128.2, 128.5, 128.7, 128.8, 129.2, 129.2, 130.4, 130.8, 131.1, 132.0, 132.2, 137.1, 141.5, 146.7, 146.8, 149.1, 149.3 (Ar); ^{31}P NMR ($CDCl_3$) δ: 82.7 ($^1J_{P\text{-}Se}$ = 981.2 Hz); ^{77}Se NMR ($CDCl_3$) δ: −256.9 ($^1J_{Se\text{-}P}$ = 981.2 Hz); MS (EI) m/z: 577 (M^+); Anal. Calcd for. $C_{33}H_{24}NO_2PSe$ (577.07): C, 68.75; H, 4.20; N, 2.43. Found: C, 68.95; H, 4.44; N, 2.45.

*(R_{ax})-N,N-Bis[2-pyridinylmethyl]-dinaphtho[2,1-d:1′,2′-f][1,3,2]dioxaphosphepine-4-amine-4-selenide (***5d***).* Colorless solid; mp: 261–264°C; IR (KBr): 3056, 2923, 1620, 1589, 1570, 1508, 1462, 1432, 1361, 1324, 1290, 1255, 1223, 1192, 1134, 1113, 1088, 1068, 1050, 994, 956, 939, 841, 812, 788, 762, 749, 711, 696, 652, 627, 614, 574, 564, 520, 501, 488, 455, 418 cm^{-1}; ^1H NMR ($CDCl_3$) δ: 4.15 (t, J = 16.1 Hz, 2H, CH_2Py), 4.72 (dd, $^3J_{H\text{-}P}$ = 16.0 Hz, $^2J_{H\text{-}H}$ = 10.4 Hz, 2H, CH_2Py), 7.03–8.55 (m, 20H, Ar); ^{13}C NMR ($CDCl_3$) δ: 53.2 (CH_2Py), 120.6, 121.7, 121.9, 122.3, 122.5, 125.7, 126.5, 126.7, 127.0, 128.5, 130.8, 131.0, 131.4, 131.9, 132.2, 132.4, 136.8, 146.8, 146.9, 148.7, 148.8, 149.3, 157.0 (Ar); ^{31}P NMR ($CDCl_3$) δ: 88.1 ($^1J_{P\text{-}Se}$ = 976.4 Hz); ^{77}Se NMR ($CDCl_3$) δ: −300.8 ($^1J_{Se\text{-}P}$ = 976.4 Hz); MS (EI) m/z: 593 (M^+); Anal Calcd for $C_{32}H_{24}N_3O_2PSe$ (593.08): C, 64.87; H, 4.08; N, 7.09. Found: C, 64.73; H, 4.18; N, 6.99.

*(R_{ax})-1(4-Selenidodinaphtho[2,1-d:1′,2′-f][1,3,2]-dioxaphosphepin-4-yl)-2-methoxymethyl-(2S)-pyrrolidine ((R_{ax},S) (***5e***).* Colorless solid; mp: 112–118°C; IR (KBr): 3054, 2925, 2874, 1619, 1588, 1507, 1461, 1323, 1102, 1067, 952, 834, 811, 750, 696, 624, 584,

566, 523 cm^{-1}; ^1H NMR ($CDCl_3$) δ: 1.73 (m, 2H, $NCH_2C\underline{H}_2$), 1.89 (m, 2H, $NCHC\underline{H}_2$), 2.58 (m, 1H, NCH_2), 3.20 (m, 1H, NCH_2), 3.43 (s, 3H, OCH_3), 3.53 (dd, J = 7.2 Hz, $^2J_{H\text{-}H}$ = 9.6 Hz, 1H, OCH_2), 3.65 (dd, J = 4.4 Hz, $^2J_{H\text{-}H}$ = 9.6 Hz, 1H, OCH_2), 4.15 (m, 1H, NCH), 7.24–8.04 (m, 12H, Ar); ^{13}C NMR ($CDCl_3$) δ: 25.3 (d, $^3J_{C\text{-}P}$ = 7.2 Hz, $NCH_2\underline{C}H_2$), 28.1 (d, $^3J_{C\text{-}P}$ = 10.2 Hz, $NCH_2CH_2\underline{C}H_2$), 49.4 ($NCH_2$), 59.0, 60.5 (d, J = 7.3 Hz, NCH or OCH_2), 75.1 (OCH_3), 120.8, 120.9, 121.7, 122.2, 122.3, 125.5, 125.6, 126.4, 126.6, 127.1, 128.4, 128.5, 130.6, 130.7, 131.4, 131.8, 132.2, 132.3, 132.4, 146.8, 146.9, 148.5, 148.7 (Ar); ^{31}P NMR ($CDCl_3$) δ: 80.6 ($^1J_{P\text{-}Se}$ = 962.9 Hz); ^{77}Se NMR ($CDCl_3$) δ: −277.8 (d, $^1J_{Se\text{-}P}$ = 962.9 Hz); MS (EI) m/z: 509 (M^+); HRMS Calcd for $C_{26}H_{24}NO_3PSe$: 509.0659. Found: 509.0656.

Typical Procedure for the Fluoride-Ion-Mediated Hydrolysis of Amides and Ester

To a dry THF solution (1 mL) of **5a** (591 mg, 1.0 mmol) was added TBAF (1 M, THF) (4.0 mL, 4.0 mmol) at room temperature under an Ar atmosphere. The resulting solution was stirred at room temperature for 2 h and concentrated in vacuo. The reaction mixture was purified by column chromatography on silica gel (CH_2Cl_2 100% and EtOAc 100%, $Rf_{CH_2Cl_2}$ = 0.10, Rf_{EtOAc} = 0.38) to give *N,N,N*-tributyl-1-butanaminium-*O*-(1R)-2′-hydroxy[1,1′-binaphthalene]-2-yl-[*N,N*-bis-(phenylmethyl)]phosphonoselenoate (**7a**) (380 mg, 45%) as a colorless solid.

IR (KBr): 3444, 2960, 1593, 1456, 1377, 1220, 1146, 1069, 948, 821, 792, 745, 698, 591, 563, 494, 445 cm^{-1}; ^1H NMR ($CDCl_3$) δ: 0.72 (t, J = 7.2 Hz, 10H, $C\underline{H}_3$), 1.07 (sex, J = 7.2 Hz, 6H, $C\underline{H}_2CH_3$), 1.32 (m, 6H, $NCH_2C\underline{H}_2$), 2.92 (m, 6H, $NC\underline{H}_2CH_2$), 3.65 (dd, $^2J_{H\text{-}H}$ = 15.8 Hz, $^3J_{H\text{-}P}$ = 12.4 Hz, 2H, $C\underline{H}_2Ph$), 4.11 (dd, $^2J_{H\text{-}H}$ = 15.8 Hz, $^3J_{H\text{-}P}$ = 11.6 Hz, 2H, $C\underline{H}_2Ph$), 6.77–7.75 (m, 21H, Ar), 8.51 (d, J = 8.8 Hz, 1H, Ar); ^{13}C NMR ($CDCl_3$) δ: 13.6 ($\underline{C}H_3$), 19.5 ($\underline{C}H_2CH_3$), 24.0 ($NCH_2\underline{C}H_2$), 48.4 (d, $^2J_{C\text{-}P}$ = 5.3 Hz, $\underline{C}H_2Ph$), 58.6 ($N\underline{C}H_2$), 119.6, 121.2, 122.5, 123.0, 124.3, 124.6, 125.4, 125.8, 125.9, 127.6, 127.7, 128.2, 129.1, 129.4, 130.1, 134.2, 134.4, 139.0, 150.5, 150.6, 152.7 (Ar); ^{31}P NMR ($CDCl_3$) δ: 55.1 ($^1J_{P\text{-}Se}$ = 761 Hz); ^{77}Se NMR ($CDCl_3$) δ: −168.4 (d, $^1J_{Se\text{-}P}$ = 761 Hz); MS (FAB^-) m/z: 608 ($M^+ - Bu_4$).

General Procedure for the Methylation of Salts

To dry THF (1 mL) or dry Et_2O (1 mL) solutions of the salts was added MeI (4 equiv) at room temperature under an Ar atmosphere. The resulting solutions were stirred at room temperature for 2 h and concentrated in vacuo. The reaction mixture was purified by column chromatography on silica gel (EtOAc:hexane = 1:1, Rf = 0.80) to give the corresponding esters.

*N,N-Bis(phenylmethyl)phosphoramidoselenoic Acid O-(1R)-2′-Hydroxy[1,1′-binaphthalene]-2-yl Semethyl Ester (**9a**).* A colorless solid; mp: 75–82°C; IR (KBr): 3244, 3060, 2923, 1621, 1592, 1506, 1455, 1347, 1275, 1207, 1066, 993, 946, 815, 746, 698, 605, 496, 446 cm^{-1}; ^1H NMR ($CDCl_3$) δ: 1.91 (d, $^2J_{H\text{-}P}$ = 14.0 Hz, 3H, $SeC\underline{H}_3$), 3.51 (dd, $^2J_{H\text{-}H}$ = 15.6 Hz, $^3J_{H\text{-}P}$ = 11.6 Hz, 2H, $C\underline{H}_2Ph$), 3.65 (dd, $^2J_{H\text{-}H}$ = 15.6 Hz, $^3J_{H\text{-}P}$ = 11.6 Hz, 2H, $C\underline{H}_2Ph$), 6.04 (m, 1H, OH), 6.81–7.98 (m, 22H, Ar); ^{13}C NMR ($CDCl_3$) δ: 5.54 (d, $^2J_{C\text{-}P}$ = 4.9 Hz, $Se\underline{C}H_3$), 47.5 (d, $^2J_{C\text{-}P}$ = 4.8 Hz, $\underline{C}H_2Ph$), 115.4, 119.3, 120.5, 122.6, 123.5, 124.9, 125.9, 126.6, 127.3, 127.4, 128.0, 128.3, 129.1, 130.0, 130.6, 131.6, 133.5, 133.9, 136.2, 147.5, 147.6, 152.1 (Ar); ^{31}P NMR ($CDCl_3$) δ: 26.9 (d, $^1J_{P\text{-}Se}$ = 463 Hz); ^{77}Se NMR ($CDCl_3$) δ: 89.9 (d, $^1J_{Se\text{-}P}$ = 463 Hz); MS (EI) m/z: 622 (M^+); HRMS Calcd for $C_{35}H_{30}NO_3PSe$: 623.1129. Found: 623.1130.

*Tetra-n-butylammonium Salt with N,N-Diphenylphosphoramidofluoridoselenoic Acid (**6b**).* ^1H NMR ($CDCl_3$) δ: 0.91 (t, J = 7.0 Hz, 12H, $CH_2CH_2C\underline{H}_3$), 1.32 (m, 8H, $CH_2C\underline{H}_2Me$), 1.48 (m, 8H, CH_2Et), 3.09 (m, 9H, CH_2Pr), 6.85–7.35 (m, 10H, Ar); ^{31}P NMR ($CDCl_3$) δ: 41.9 (dd, $^1J_{P\text{-}F}$ = 1095.4 Hz, $^1J_{P\text{-}Se}$ = 830.4 Hz).

*Tetra-n-butylammonium Salt with N-Phenyl-N-phenylmethylphosphoramidofluoridoselenoic Acid (**6c**).* ^1H NMR ($CDCl_3$): δ 0.85 (m, 15H, $CH_2CH_2C\underline{H}_3$), 1.25 (m, 10H, $CH_2C\underline{H}_2Me$), 1.45 (m, 10H, CH_2Et), 3.07 (m, 10H, CH_2Pr), 4.82 (dd, $^2J_{H\text{-}H}$ = 16.0 Hz, $^3J_{H\text{-}P}$ = 10.0 Hz, 1H, $NC\underline{H}_2$), 4.94 (dd, $^2J_{H\text{-}H}$ = 16.0 Hz, $^3J_{H\text{-}P}$ = 10.4 Hz, 1H, $NC\underline{H}_2$), 6.84–7.30 (m, 10H, Ar); ^{31}P NMR ($CDCl_3$): δ 47.9 (dd, $^1J_{P\text{-}F}$ = 1089.5 Hz, $^1J_{P\text{-}Se}$ = 815.6 Hz).

*N,N,N-Tributyl-1-butanaminium-O-(1R)-2′-hydroxy[1,1′-binaphthalene]-2-yl-[N,N-bis-(2-pyridinylmethyl)]phosphonoselenoate (**7d**).* IR (KBr): 3407, 3055, 2959, 1593, 1471, 1436, 1334, 1219, 1148, 1070, 963, 934, 790, 693, 570 500 cm^{-1}; ^1H NMR ($CDCl_3$) δ: 0.75 (t, J = 7.2 Hz, 9H, $C\underline{H}_3$), 1.13 (m, 6H, $C\underline{H}_2CH_3$), 1.39 (m, 6H, $NCH_2C\underline{H}_2$), 3.04 (m, 6H, $NC\underline{H}_2CH_2$), 3.91 (m, 2H, $C\underline{H}_2Ph$), 4.33 (m, 2H, $C\underline{H}_2Ph$), 6.77–7.73 (m, 17H, Ar), 8.15 (d, J = 4.0 Hz, 2H, Ar), 8.48 (d, J = 8.4 Hz, 1H, Ar); ^{31}P NMR ($CDCl_3$) δ: 56.4 ($^1J_{P\text{-}Se}$ = 1086 Hz); MS (FAB^-) m/z: 608 (M^+–Bu_4).

N,N,N-Tributyl-1-butanaminium-O-(1R)-2′-hydroxy[1,1′-binaphthalene]-2-yl-1-[2-methoxymethyl-(2S)-pyrrolidinyl]-phosphonoselenoate (**7e**). ^{1}H NMR ($CDCl_3$) δ: 0.75 (t, J = 7.4 Hz, 20H, C$\underline{H}_3$), 1.23 (m, 12H, C$\underline{H}_2$CH$_3$), 1.47 (m, 15H, NCH$_2$C$\underline{H}_2$), 1.77 (m, 2H, NCHC$\underline{H}_2$ or CHCH$_2$C$\underline{H}_2$), 2.56 (m, 1H, PNCH$_2$), 2.65 (m, 1H, PNC$\underline{H}_2$), 3.05 (s, 3H, OCH$_3$), 3.10 (m, 15H, C$\underline{H}_2$NC$\underline{H}_2$), 3.30 (m, 2H, OCH$_2$), 3.76 (m, 1H, NCH), 6.88–7.33 (m, 6H, Ar), 7.74–7.81 (m, 5H, Ar), 8.52 (d, J = 8.8 Hz, 1H, Ar); ^{31}P NMR ($CDCl_3$) δ: 53.1 ($^1J_{P\text{-}Se}$ = 758 Hz) The signals due to NCHC$\underline{H}_2$ were overlapped with those due to NCH$_2$CH$_2$CH$_2$CH$_3$.

N,N-Diphenylphosphoramidofluoridoselenoic Acid Se-methyl Ester (**8b**). A yellow oil; IR (neat): 3062, 2940, 1588, 1490, 1287, 1258, 1202, 1075, 1036, 992, 889, 842, 755, 697, 615, 557 499 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ: 2.25 (dd, $^3J_{H\text{-}P}$ = 15.2 Hz, J = 1.6 Hz, 3H, SeC$\underline{H}_3$), 7.15–7.29 (m, 10H, Ar); ^{13}C NMR ($CDCl_3$) δ: 5.5 (dd, $^2J_{C\text{-}P}$ = 5.4 Hz, $^1J_{C\text{-}Se}$ = 0.95 Hz, Se$\underline{C}$H$_3$), 126.8, 127.0, 127.1, 129.5, 141.6 (Ar); ^{19}F NMR ($CDCl_3$) δ: −31.4 (dd, $^1J_{F\text{-}P}$ = 1153 Hz, $^2J_{F\text{-}Se}$ = 53.2 Hz); ^{31}P NMR ($CDCl_3$) δ: 19.5 (dd, $^1J_{P\text{-}F}$ = 1153 Hz, $^1J_{P\text{-}Se}$ = 530 Hz); ^{77}Se NMR ($CDCl_3$) δ: 111.2 (dd, $^1J_{Se\text{-}P}$ = 530 Hz, $^2J_{Se\text{-}F}$ = 53.2 Hz); MS (EI) *m/z*: 329 (M$^+$); HRMS Calcd for $C_{13}H_{13}FNOPSe$: 328.9884. Found: 328.9859.

N-Phenyl-N-phenylmethylphosphoramidofluoridoselenoic Acid Se-methyl Ester (**8c**). A colorless solid; IR (neat): 3032, 2939, 1596, 1493, 1455, 1284, 1251, 1097, 1068, 886, 820, 774, 695, 537 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ: 2.20 (d, $^3J_{H\text{-}P}$ = 15.2 Hz, 3H, SeC$\underline{H}_3$), 4.62 (m, 1H, NC$\underline{H}_2$), 4.79 (dd, $^2J_{H\text{-}H}$ = 15.2 Hz, $^3J_{H\text{-}P}$ = 9.2 Hz, 1H, NC$\underline{H}_2$), 7.03–7.33 (m, 10H, Ar); ^{13}C NMR ($CDCl_3$) δ: 4.8 (d, $^2J_{C\text{-}P}$ = 4.9 Hz, Se$\underline{C}$H$_3$), 54.7 (d, $^2J_{C\text{-}P}$ = 5.8 Hz, N$\underline{C}$H$_2$), 127.5, 127.7, 128.3, 128.4, 128.6, 129.4, 136.7, 139.3 (Ar); ^{19}F NMR ($CDCl_3$) δ: −30.9 (dd, $^1J_{F\text{-}P}$ = 1152 Hz, $^2J_{F\text{-}Se}$ = 51.3 Hz); ^{31}P NMR ($CDCl_3$) δ: 23.3 (dd, $^1J_{P\text{-}F}$ = 1152 Hz, $^1J_{P\text{-}Se}$ = 517 Hz); ^{77}Se NMR ($CDCl_3$) δ: 97.2 (dd, $^1J_{Se\text{-}P}$ = 517 Hz, $^2J_{Se\text{-}F}$ = 51.3 Hz); MS (EI) *m/z*: 343 (M$^+$); HRMS Calcd for $C_{14}H_{15}FNOP^{82}Se$: 345.0042. Found: 345.0020.

N-Phenyl-N-phenylmethylphosphoramidoselenoic Acid O-(1R)-2′-Hydroxy[1,1′-binaphthalene]-2-yl Se-methyl Ester (**9c**). A yellow solid; mp: 72–77°C; IR (neat): 3238, 3059, 2932, 1621, 1593, 1493, 1455, 1433, 1329, 1276, 1207, 1068, 990, 881, 815, 749, 695, 604, 529 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ: 1.96 (d, $^3J_{H\text{-}P}$ = 13.6 Hz, 3H, SeC$\underline{H}_3$), 4.10 (m, 2H, C$\underline{H}_2$Ph), 6.49–7.97 (m, 22H, Ar); ^{13}C NMR ($CDCl_3$) δ: 5.7 (d, $^2J_{C\text{-}P}$ = 4.9 Hz, Se$\underline{C}$H$_3$), 53.4 (d, $^2J_{C\text{-}P}$ = 4.8 Hz, $\underline{C}$H$_2$Ph), 116.4, 119.9, 120.2, 123.0, 123.1, 123.6, 124.9, 125.9, 126.5, 126.6, 127.1, 127.4, 128.0, 128.2, 128.3, 128.7, 129.3, 129.5, 130.1, 130.6, 130.8, 131.6, 133.8, 136.7, 140.0, 147.5, 147.6, 152.4 (Ar); ^{31}P NMR ($CDCl_3$) δ: 24.0 (d, $^1J_{P\text{-}Se}$ = 476 Hz); ^{77}Se NMR ($CDCl_3$) δ: 98.8 (d, $^1J_{Se\text{-}P}$ = 476 Hz); MS (EI) *m/z*: 609 (M$^+$); HRMS Calcd for $C_{34}H_{28}NO_3PSe$: 609.0972. Found: 609.0975.

N,N-Bis[2-pyridinylmethyl]phosphoramidoselenoic Acid O-(1R)-2′-Hydroxy[1,1′-binaphthalene]-2-yl Se-methyl Ester (**9d**). A colorless solid; mp: 82–92°C; IR (KBr): 3203, 3055, 2931, 1733, 1621, 1592, 1505, 1474, 1435, 1346, 1212, 1146, 1071, 994, 937, 817, 749, 661, 606, 513, 445 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ: 1.73 (d, $^3J_{H\text{-}P}$ = 14.4 Hz, 3H, SeC$\underline{H}_3$), 3.89 (dd, $^2J_{H\text{-}H}$ = 15.6 Hz, $^3J_{H\text{-}P}$ = 12.0 Hz, 2H, C$\underline{H}_2$Py), 4.30 (dd, $^2J_{H\text{-}H}$ = 15.6 Hz, $^3J_{H\text{-}P}$ = 12.4 Hz, 2H, C$\underline{H}_2$Py), 6.92–7.94 (m, 20H, Ar); ^{13}C NMR ($CDCl_3$) δ: 5.04 (d, $^2J_{C\text{-}P}$ = 5.3 Hz, Se$\underline{C}$H$_3$), 50.7 (d, $^2J_{C\text{-}P}$ = 4.8 Hz, $\underline{C}$H$_2$Ph), 115.1, 119.5, 120.0, 122.3, 123.0, 123.3, 124.9, 125.5, 126.0, 127.1, 127.9, 128.0, 128.8, 129.9, 130.0, 131.2, 133.9, 136.7, 148.7, 153.0, 156.2, 156.3 (Ar); ^{31}P NMR ($CDCl_3$) δ: 26.0 (d, $^1J_{P\text{-}Se}$ = 482 Hz); ^{77}Se NMR ($CDCl_3$) δ: 101.9 (d, $^1J_{Se\text{-}P}$ = 482 Hz); MS (EI) *m/z*: 626 (M$^+$); Anal. Calcd for. $C_{33}H_{28}N_3O_3PSe{\cdot}0.5H_2O$: C, 62.56; H, 4.61; N, 6.63. Found: C, 62.76; H, 4.38; N, 6.50.

1-[2-Methoxymethyl-(2S)-pyrrolidinyl]-phosphonoselenoic Acid O-(1R)-2′-Hydroxy[1,1′-binaphthalene]-2-yl Se-methyl Ester (**9e**). A colorless solid; mp: 62–69°C; IR (KBr): 3220, 3063, 2934, 1622, 1592, 1506, 1461, 1433, 1346, 1275, 1220, 1105, 1070, 993, 816, 748, 661, 603, 561, 531 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ: 1.42–1.68 (m, 4H, NCH$_2$C$\underline{H}_2$), 1.98 (dd, $^3J_{H\text{-}P}$ = 13.4 Hz, J = 1.8 Hz, 3H, SeCH$_3$), 2.45 (m, 1H, NCH$_2$), 2.57 (m, 1H, NCH$_2$), 2.90 (dd, $^4J_{H\text{-}P}$ = 7.2 Hz, $^2J_{H\text{-}H}$ = 9.6 Hz, 1H, OCH$_2$), 3.05 (dd, $^4J_{H\text{-}P}$ = 4.0 Hz, $^2J_{H\text{-}H}$ = 9.6 Hz, 1H, OCH$_2$), 3.06 (s, 3H, OCH$_3$), 3.32 (m, 1H, NCH), 7.04–8.02 (m, 12H, Ar); ^{13}C NMR ($CDCl_3$) δ: 5.01 (d, $^2J_{C\text{-}P}$ = 4.9 Hz, SeCH$_3$), 2.45 (d, $^3J_{C\text{-}P}$ = 8.3 Hz, NCH$_2$C$\underline{H}_2$), 28.8 (d, $^3J_{C\text{-}P}$ = 7.8 Hz, N CH$_2$CH$_2$C$\underline{H}_2$), 47.2 (d, $^2J_{C\text{-}P}$ = 3.9 Hz, NCH$_2$), 57.5 (d, J = 3.9 Hz, NCH$_2$ or OCH$_2$), 58.7 (NCH$_2$ or OCH$_2$), 74.6 (OCH$_3$), 116.0, 119.5, 120.6, 122.7, 123.5, 124.9, 125.8, 126.5, 127.3, 127.9, 128.2, 129.1, 130.0, 130.5, 131.5, 133.7, 147.4, 147.5, 125.3 (Ar); ^{31}P NMR ($CDCl_3$) δ: 25.5 ($^1J_{P\text{-}Se}$ = 464.2 Hz); ^{77}Se NMR ($CDCl_3$) δ: 77.3 (d, $^1J_{Se\text{-}P}$ = 464.2 Hz); MS (EI) *m/z*: 509 (M$^+$); HRMS Calcd for $C_{27}H_{28}NO_4PSe$: 541.0921. Found: 541.0948.

Tetrabutylammonium L-Methylphosphorofluoroselenoic Acid (**14**). IR (neat): 2925, 2363, 2343,

2206, 1718, 1637, 1596, 1458, 1384, 1200, 1107, 1019, 930, 881, 820, 606, 576, 521, 481, 820, 606, 576, 521, 481, 471, 445, 433, 419, 406 cm^{-1}; ^1H NMR ($CDCl_3$) δ: 0.78 (d, $J = 6.8$ Hz, 3H, CH_3), 0.82 (d, $J = 7.3$ Hz, 3H, CH_3), 0.83 (d, $J = 6.3$ Hz, 3H, CH_3), 0.72–0.83 (m, 1H), 0.96 (t, $J = 7.3$ Hz, 12H, $CH_2C\underline{H}_3$), 0.92–1.04 (m, 2H), 1.41 (sex, $J = 7.3$ Hz, 8H, $C\underline{H}_2CH_3$), 1.19–1.66 (m, 4H, CH_2 and/or CH), 1.54–1.66 (m, 8H, $C\underline{H}_2CH_2CH_3$), 2.20–2.28 (m, 1H), 2.37–2.40 (m, 1H), 3.26–3.30 (m, 8H, NCH_2), 4.21 (ddt, $J = 10.9$ Hz, $J = 6.3$ Hz, $J = 4.5$ Hz, 1H, OCH); ^{13}C NMR ($CDCl_3$) δ: 13.7, 16.0, 19.7, 21.2, 22.1, 22.9, 24.1, 25.2, 31.5, 34.5, 43.0, 48.5 (d, $J = 6.6$ Hz), 58.8, 77.3 (d, $^2J_{C\text{-}P} = 8.3$ Hz); ^{19}F NMR ($CDCl_3$) δ: −16.8 (d, $^1J_{P\text{-}F} = 1109.9$ Hz, $^2J_{F\text{-}Se} = 136.1$ Hz); ^{31}P NMR ($CDCl_3$) δ: 41.8 (dd, $^1J_{P\text{-}F} = 1109.9$ Hz, $^1J_{P\text{-}Se} = 848.1$ Hz); ^{77}Se NMR ($CDCl_3$) δ: −247.6 (dd, $^1J_{P\text{-}Se} = 848.1$ Hz, $^2J_{F\text{-}Se} = 136.1$ Hz); MS (FAB^-) *m/z*: 301 (M^+–Bu_4).

*A Mixture of Diastereomers of L-Menthylphosphorofluoridoselenoic Acid Se-methyl Ester (***16***).* IR (neat); 3410, 2961, 2929, 2868, 2338, 1701, 1455, 1427, 1388, 1370, 1351, 1290, 1264, 1218, 1081, 1060, 1000, 932, 916, 881, 849, 822, 806, 563, 545, 504, 493, 424, 407 cm^{-1}; ^1H NMR ($CDCl_3$) δ :0.806 (d, $J = 6.8$ Hz, 3H, CH_3), 0.809 (d, $J = 6.8$ Hz, 3H, CH_3), 0.89 (m, 6H, CH_3, m, 6H, CH_3), 0.78–0.92 (m, 1H, m, 1H), 0.94–1.06 (m, 1H, m, 1H), 1.17–1.28 (m, 1H, m, 1H), 1.36–1.51 (m, 2H, m, 2H), 1.61–1.70 (m, 2H, m, 2H), 1.98–2.10 (m, 1H, m, 1H), 2.291 (d, $J = 16.4$ Hz, 3H, $SeCH_3$), 2.294 (d, $J = 15.6$ Hz, 3H, $SeCH_3$), 2.17–2.32 (m, 1H, m, 1H), 4.39–4.51 (m, 1H, OCH, m, 1H, OCH); ^{13}C NMR ($CDCl_3$) δ: 5.0 (d, $J = 5.8$ Hz, $SeCH_3$), 5.1 (d, $J = 5.8$ Hz, $SeCH_3$), 15.7, 15.8, 20.8, 20.9, 21.8, 21.9, 23.0, 23.0, 25.7, 25.9, 31.6, 31.7, 33.79, 33.81, 42.4, 42.8, 48.2 (d, $J = 7.4$ Hz), 48.3 (d, $J = 6.6$ Hz), 82.3 (d, $^2J_{C\text{-}P} = 11.6$ Hz, O$\underline{C}$H), 82.4 (d, $^2J_{C\text{-}P} = 9.1$ Hz); ^{19}F NMR ($CDCl_3$) δ: −31.6 (dd, $^1J_{P\text{-}F} = 1173.0$ Hz, $^2J_{F\text{-}Se} = 72.2$ Hz), −33.8 (dd, $^1J_{P\text{-}F} = 1173.0$ Hz, $^2J_{F\text{-}Se} = 72.2$ Hz); ^{31}P NMR ($CDCl_3$) δ: 16.0 (dd, $^1J_{P\text{-}F} = 1173.0$ Hz, $^1J_{P\text{-}Se} = 558.5$ Hz), 14.8 (dd, $^1J_{P\text{-}F} = 1173.0$ Hz, $^1J_{P\text{-}Se} = 558.5$ Hz); ^{77}Se NMR ($CDCl_3$) δ: 87.1 (dd, $^1J_{P\text{-}Se} = 558.5$ Hz , $^2J_{F\text{-}Se} = 72.2$ Hz), 73.4 (dd, $^1J_{P\text{-}Se} = 558.5$ Hz , $^2J_{F\text{-}Se} = 72.2$ Hz); MS (EI) *m/z*: 316 (M^+); HRMS Calcd for $C_{11}H_{22}O_2PSe$: 316.0507. Found: 316.0513.

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