A Novel and General Method for the Formation of *S*-Aryl, *Se*-Aryl, and *Te*-Aryl Phosphorochalcogenoates

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Abstract: A new and general method for the synthesis of *S*-, *Se*-, and *Te*-aryl phosphorochalcogenoates (chalcogenophosphates) has been developed. S–P, Se–P, and Te–P bonds were formed by the coupling of readily available dialkyl phosphites with diaryl dichalcogenides at 30 °C in dimethyl sulfoxide in the presence of catalytic amounts of copper iodide and diethylamine. The reaction proceeded smoothly without exclusion of moisture or air.

Key words: Lewis acids, selenium, phosphorylation, sulfur, tellurium

S-, *Se*-, and *Te*-Aryl phosphorochalcogenoates (chalcogenophosphates) are very useful synthetic intermediates for a variety of natural and complex molecules.[1] *S*-Aryl phosphorothioates can be used to construct an intramolecular pyrophosphate linkage,[1d–1f] hydroxy group,[2] thiophosphorylation of terminal alkynes,[3] and dialkyl (2-sulfanylphenyl)phosphonates.[4] Likewise, *Se*-aryl phosphoroselenoates have attracted much attention over the last few decades.[1b,5] Han and co-workers reported the palladium-catalyzed selenophosphorylation of terminal alkynes[1a] with aryl phosphoroselenoates.

Most of the methodologies for the synthesis of *S*-, *Se*-, and *Te*-aryl phosphorochalcogenoates have involved special reagents sensitive to air or moisture, thus they must be performed under strict reaction conditions and this limits their application.[1b,4,6,7] Huang prepared *Se*-aryl phosphoroselenoates successfully using 2,2′-azobis(isobutyronitrile) as a catalyst, but *Te*-organyl phosphorotelluroates and *S*-organyl phosphorothioates were formed in very low yield using a similar method.[8,9] An alternative preparation of *Te*-aryl phosphorotelluroates in good yields was reported that used 4-methoxyphenyltellurium trichloride and dialkyl or trialkyl phosphites.[4] To the best of our knowledge, there is no general and efficient method for the synthesis of S–P, Se–P, and Te–P bonds. Considering the growing utility of organotellurium compounds in organic synthesis,[10] limited studies have been performed related to the preparation of *Te*-aryl phosphorotelluroates. Therefore, the development of a general, efficient, and economic method for the preparation of *S*-, *Se*-, and *Te*-aryl phosphorochalcogenoates is highly desirable.

Of late, the synthesis of (phenylselanyl)alkynes[11] employing copper iodide as a catalyst, prompted us to investigate the synthesis of *S*-, *Se*-, and *Te*-aryl phosphorochalcogenoates using Lewis acids. We report here that *S*-, *Se*-, and *Te*-aryl phosphorochalcogenoates can be conveniently prepared using a novel copper(I) iodide catalyzed cross-coupling reaction between various dialkyl phosphites and diaryl dichalcogenides.

We first attempted the coupling of diisopropyl phosphite with diphenyl disulfide at 30 °C in dimethyl sulfoxide in the presence of 0.03 equivalents of copper(I) iodide under an air atmosphere, but no reaction was observed even after 20 hours (Table 1, entry 1). However, when potassium carbonate (1.0 equiv) was added as a base, the reaction afford the corresponding *O*,*O*-diisopropyl *S*-phenyl phosphorothioate (**3a**) in 51% yield (Table 1, entry 2). This interesting result promoted us to try other bases; it was found that among all the bases examined, diethylamine produced the best yield of **3a** (Table 1, entry 6). Inorganic bases gave low yields because of their poor solubility. Pyridine gave only a 10% isolated yield possibly because it is a very weak base. Interestingly, we found that the decreasing the amount of diethylamine from 1.0 to 0.2 equivalents had no noticeable impact on the yield (Table 1, entry 6–8) and, in fact, 0.2 equivalents of diethylamine was sufficient to produce a good yield of **3a**.

Using compound **3a** as a model reaction, we studied the effect of the solvent on the reaction using dimethyl sulfoxide, tetrahydrofuran, acetonitrile, dichloromethane, and toluene (Table 1, entries 8, 10–12); we found that dimethyl sulfoxide was the best solvent (Table 1, entry 8). On the other hand, the copper(I) iodide catalyzed reaction also gave a good result in the absence of air or oxygen, probably because dimethyl sulfoxide could act not only as the solvent, but also as an oxidant.[11,12]

To investigate the suitability of copper(I) iodide for the preparation of *S*-organyl phosphorothioates, we evaluated several common Lewis acids, including copper(I) chloride, copper(II) chloride, copper(I) bromide in order to assess their ability to catalyze S–P bond formation (Table 1, entries 15–17). Our results showed that both copper(I) and iodide ions are needed to optimize the formation of the S–

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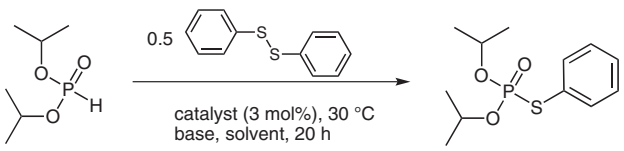
Table 1 Compound **3a** Prepared Under Various Conditions



3a

Entry	Catalyst	Solvent	Base (equiv)	Yield[b] (%)
1	CuI	DMSO	–	0
2	CuI	DMSO	K_2CO_3 (1.0)	51
3	CuI	DMSO	K_2HPO_4 (1.0)	15
4	CuI	DMSO	pyridine (1.0)	10
5	CuI	DMSO	Et_3N (1.0)	78
6	CuI	DMSO	Et_2NH (1.0)	90
7	CuI	DMSO	Et_2NH (0.6)	92
8	CuI	DMSO	Et_2NH (0.2)	93
9	CuI	DMSO	Et_2NH (0.1)	73
10	CuI	MeCN	Et_2NH (0.2)	52
11	CuI	THF	Et_2NH (0.2)	40
12	CuI	CH_2Cl_2	Et_2NH (0.2)	27
13	CuI	toluene	Et_2NH (0.2)	36
14	–	DMSO	Et_2NH (0.2)	31
15	CuBr	DMSO	Et_2NH (0.2)	87
16	CuCl	DMSO	Et_2NH (0.2)	79
17	$CuCl_2$	DMSO	Et_2NH (0.2)	64

[a] Reaction conditions: $(i\text{-PrO})_2POH$ (0.3 mmol), $(PhS)_2$ (0.15 mmol), catalyst (0.03 equiv), solvent (1 mL).
[b] Isolated yield based on $(i\text{-PrO})_2POH$.

P bond. Without a catalyst (Table 1, entry 14), the reaction occurs, but the yield was much lower.

To demonstrate the generality of this method, a series of dialkyl phosphites and diaryl disulfides were used (Table 2). We found that these reactions took place rapidly and gave the corresponding *S*-aryl phosphorothioates **3b–j** in good to excellent yields (Table 2, entries 1–9). These results showed that diaryl disulfides with an electron-withdrawing group on the phenyl group (Table 2, entries 1–3), were less reactive than those with an electron-donating group (Table 2, entries 5–7). Variation in the *H*-phosphonate substituent from a short-chain alkyl to a long-chain alkyl did not affect the course of the construction of S–P bonds. Noteworthy was that more hindered dihexyl phosphite was well tolerated and gave good yields of *S*-aryl *O*,*O*-dihexyl phosphorothioates **3i,j** (Table 2, entries 8 and 9).

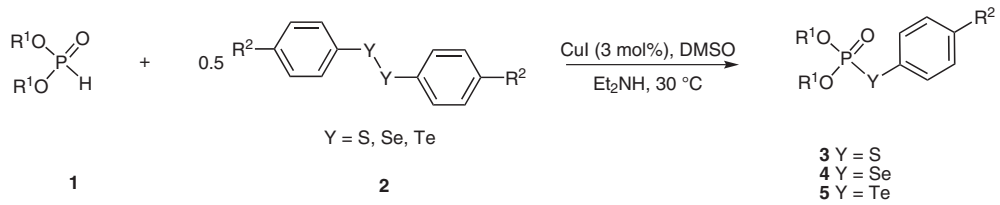
Encouraged by these results, we examined similar reactions using diaryl diselenides and diaryl ditellurides as substrates. Various diaryl diselenides gave the desired products **4a–i** in good yields, without noticeable differences observed in the reaction temperature or time, compared with the results from *S*-aryl phosphorothioates (Table 2, entries 10–18). Nevertheless, we found that an increase in the amount of diethylamine was necessary when the substrates were diaryl ditellurides, or longer reaction times were required. For example, the cross-coupling of diisopropyl phosphite with diphenyl ditelluride using 0.2 equivalents of diethylamine afforded the corresponding product **5a** in 80% isolated yield after stirring for 45 hours (Table 2, entry 19); when 0.4 equivalents of diethylamine were used, the reaction time decreased to 25 hours and the yield of **5a** increased to 85% (Table 2, entry 19). Other *Te*-aryl phosphorotelluroates **5b–e** were obtained in moderate yields under the above conditions (Table 2, entries 21–21). The reaction of diethyl phosphite with diphenyl ditelluride gave a low yield due to decomposition of the product **5c**.[8,13] The structures of the *Se*-aryl phosphoroselenoates and *Te*-aryl phosphorotelluroates were confirmed by ^1H, ^{13}C, and ^{31}P NMR and ESI-MS analysis. Characteristic ^{77}Se and ^{125}Te satellite peaks were observed in the ^{31}P NMR spectra with large coupling constants ($^1J_{P\text{-}Se}$ = 448–497 and $^1J_{P\text{-}Te}$ = 1340–1577 Hz) that indicated the direct connection between the phosphorus and selenium or tellurium atoms.[8] A characteristic isotopic fingerprint around calculated molecular mass weights in their ESI-MS spectra also supported the expected structure.

Finally, this method was applied to the synthesis of the nucleotide sulfide **10** and selenide **11** from ribonucleoside (Scheme 1). It was worth noting that the reaction proceeded smoothly to afford the corresponding products in 92% and 90% isolated yields.

In conclusion, under weakly basic conditions, S–P, Se–P, and Te–P bonds were formed by the coupling of readily available dialkyl phosphites with diaryl dichalcogenides. The reaction proceeded smoothly at 30 °C in the presence of a catalytic amount of copper(I) iodide and diethylamine in commercial dimethyl sulfoxide. High yields were obtained and the reaction could tolerate moisture or air. Further investigations for the elucidation of the detailed reaction mechanism and development of this methodology are currently underway in our laboratory.

All reagents were purchased from commercial sources and used without treatment, unless otherwise indicated. The products were purified by column chromatography over silica gel. ^1H and ^{13}C NMR spectra were recorded on a Bruker AV-400 spectrometer using TMS as internal standard. ^{31}P NMR spectra were recorded on the same instrument with 85% H_3PO_4 as external standard. IR spectra (KBr) were recorded on a Nicolet Avatar 360. HRMS were measured on a Bruker BioTOF-Q. ESI mass spectra were aquired on a Bruker Dalton Esquire3000 Plus mass spectrometer. Compounds **3a**,[4a] **3b**,[8] **3c**,[7h] **3e**,[7h] **3f**,[8] **4a**,[7g] **4b**,[7g] **4c**,[8] **4d**,[8] **4e**,[8] **4f**,[8] **5a**,[9] **5b**,[8] **5c**,[4b] and **5e**[4b] are known from the literature. For the new compounds, ^1H, ^{13}C, and ^{31}P NMR as well as IR, ESI-MS and HRMS data are provided.

Table 2 Preparation of Aryl Phosphorochalcogenoates



1 2

Entry	Product[a]	R^1	R^2	Y	Time (h)	Yield[b] (%)
1	**3b**	Et	H	S	20	91
2	**3c**	Et	Me	S	20	93
3	**3d**	Et	Cl	S	20	83
4	**3e**	*i*-Pr	Me	S	20	93
5	**3f**	Bu	H	S	20	92
6	**3g**	Bu	Me	S	20	94
7	**3h**	Bu	Cl	S	20	88
8	**3i**	*n*-Hex	H	S	20	92
9	**3j**	*n*-Hex	Me	S	20	95
10	**4a**	Me	H	Se	22	90
11	**4b**	Et	H	Se	22	91
12	**4c**	Et	Cl	Se	22	82
13	**4d**	*i*-Pr	Cl	Se	20	89
14	**4e**	Bu	H	Se	20	92
15	**4f**	Bu	Cl	Se	20	85
16	**4g**	*n*-Hex	H	Se	20	92
17	**4h**	*n*-Hex	Me	Se	20	93
18	**4i**	*n*-Hex	Cl	Se	20	89
19	**5a**	*i*-Pr	H	Te	45	80
20	**5a**	*i*-Pr	H	Te	25	85[c]
21	**5b**	Me	Me	Te	25	87[c]
22	**5c**	Et	H	Te	25	72[c]
23	**5d**	Et	Me	Te	25	80[c]
24	**5e**	Bu	H	Te	25	84[c]

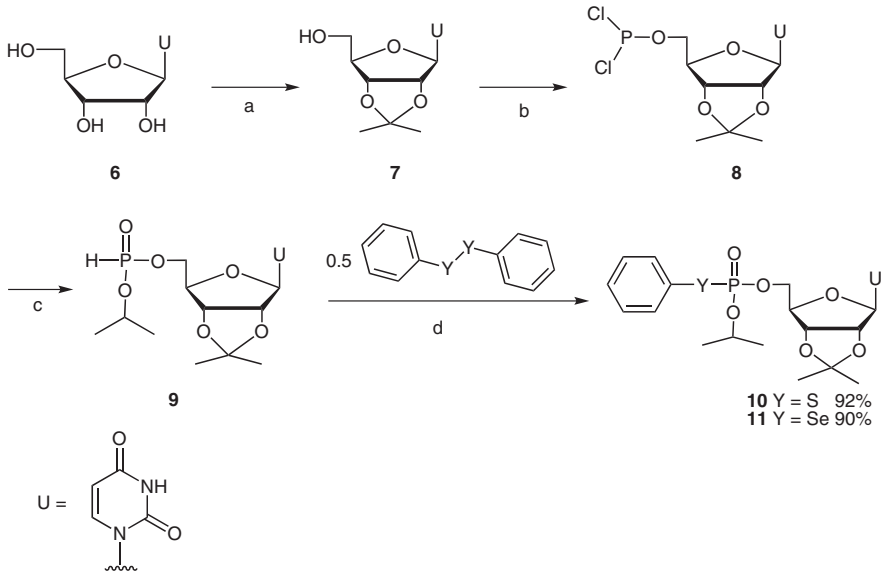
[a] All products were characterized by ^1H, ^{13}C, and ^{31}P NMR, ESI-MS, and IR.
[b] Isolated yields based on dialkyl phosphites.
[c] Et_2NH (0.4 equiv) was used.

***S*-Aryl Phosphorothioates 3a–j, *Se*-Aryl Phosphoroselenoates 4a–i, *Te*-Aryl Phosphorotelluroates 5a–e; General Procedure**

Dialkyl phosphite **1** (0.3 mmol), diaryl dichalcogenide **2** (0.15 mmol), CuI (3 mol%), and Et_2NH (0.06 or 0.12 mmol) were dissolved in commercial DMSO (1 mL) and stirred at 30 °C for the indicated time in an air atmosphere. The resulting mixture was quenched with 0.5 M AcOH and extracted with Et_2O or CH_2Cl_2. The combined organic layers were concentrated under vacuum and the crude product was purified by chromatography (silica gel, petroleum ether–EtOAc).

***O*,*O*-Dibutyl *S*-4-Tolyl Phosphorothioate (3g)**

Colorless oil.



Scheme 1 *Reagents and conditions*: (a) TsOH, acetone, reflux, 1.5 h, 95% (b) 1. PCl_3, CH_2Cl_2, –30 °C to r.t., 2. *t*-BuOH, *i*-PrOH, 0 °C, 30 min; (c) dealkylation, Et_3N, CH_2Cl_2, 0 °C, 10 min, 89%; (d) CuI (3 mol%), DMSO, Et_2NH (0.2 equiv), 30 °C.

IR (film): 3023, 2960, 2933, 2873, 1493, 1464, 1381, 1258, 1119, 1060, 1017, 983, 899, 809, 785, 727 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.44 (dd, *J* = 8.0, 1.6 Hz, 2 H), 7.15 (d, *J* = 7.9 Hz, 2 H), 4.17–4.06 (m, 4 H), 2.34 (s, 3 H), 1.66–1.59 (m, 4 H), 1.40–1.31 (m, 4 H), 0.90 (t, *J* = 7.4 Hz, 6 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 139.2 (d, J_{C-P} = 3.1 Hz, 1 C), 134.5 (d, J_{C-P} = 5.1 Hz, 2 C), 130.1 (d, J_{C-P} = 2.5 Hz, 2 C), 122.8 (d, J_{C-P} = 7.3 Hz, 1 C), 67.7 (d, J_{C-P} = 6.6 Hz, 2 C), 32.1 (d, J_{C-P} = 7.2 Hz, 2 C), 21.1 (s, 1 C), 18.6 (s, 2 C), 13.5 (s, 2 C).

^{31}P NMR (162 MHz, $CDCl_3$): δ = 23.95.

MS (ESI): *m*/*z* = 317 $[M + H]^+$, 339 $[M + Na]^+$.

HRMS (ESI-TOF): *m*/*z* $[M+ H]^+$ calcd for $C_{15}H_{25}O_3PS$: 317.1340; found: 317.1351.

O,*O*-Dibutyl *S*-4-Chlorophenyl Phosphorothioate (3h)

Colorless oil.

IR (film): 3065, 2961, 2934, 2874, 1573, 1476, 1390, 1261, 1148, 1091, 1013, 987, 900, 821, 784, 727 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.50 (dd, *J* = 6.9, 1.7 Hz, 2 H), 7.32 (d, *J* = 7.7 Hz, 2 H), 4.16–4.06 (m, 4 H), 1.67–1.60 (m, 4 H), 1.41–1.31 (m, 4 H), 0.91 (t, *J* = 7.4 Hz, 6 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 135.7 (d, J_{C-P} = 5.2 Hz, 2 C), 135.4 (d, J_{C-P} = 3.3 Hz, 1 C), 129.5 (d, J_{C-P} = 2.1 Hz, 2 C), 125.2 (d, J_{C-P} = 7.1 Hz, 1 C), 67.9 (d, J_{C-P} = 6.7 Hz, 2 C), 32.1 (d, J_{C-P} = 7.1 Hz, 2 C), 18.6 (s, 2 C), 13.5 (s, 2 C).

^{31}P NMR (162 MHz, $CDCl_3$): δ = 22.81.

MS (ESI): *m*/*z* = 337 $[M + H]^+$, 359 $[M + Na]^+$, 375 $[M + K]^+$.

HRMS (ESI-TOF): *m*/*z* $[M + H]^+$ calcd for $C_{14}H_{22}ClO_3PS$: 337.0794; found: 337.0798.

O,*O*-Dihexyl *S*-Phenyl Phosphorothioate (3i)

Colorless oil.

IR (film): 3061, 2956, 2930, 2859, 1583, 1468, 1441, 1380, 1258, 1149, 1039, 993, 856, 788, 746 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.58–7.56 (m, 2 H), 7.36–7.32 (m, 3 H), 4.17–4.04 (m, 4 H), 1.67–1.60 (m, 4 H), 1.35–1.22 (m, 12 H), 0.88 (t, *J* = 6.8 Hz, 6 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 134.4 (d, J_{C-P} = 5.2 Hz, 2 C), 129.2 (d, J_{C-P} = 2.1 Hz, 2 C), 128.8 (d, J_{C-P} = 2.6 Hz, 1 C), 126.7 (d, J_{C-P} = 7.0 Hz, 1 C), 68.1 (d, J_{C-P} = 6.6 Hz, 2 C), 31.2 (s, 2 C), 30.1 (d, J_{C-P} = 7.2 Hz, 2 C), 25.1 (s, 2 C), 22.4 (s, 2 C), 13.9 (s, 2 C).

^{31}P NMR (162 MHz, $CDCl_3$): δ = 24.63.

MS (ESI): *m*/*z* = 359 $[M + H]^+$, 381 $[M + Na]^+$.

HRMS (ESI-TOF): *m*/*z* $[M + H]^+$ calcd for $C_{18}H_{31}O_3PS$: 359.1810; found: 359.1821.

O,*O*-Dihexyl *S*-4-Tolyl Phosphorothioate (3j)

Colorless oil.

IR (film): 3023, 2956, 2929, 2859, 1493, 1467, 1380, 1257, 1120, 1039, 994, 856, 809, 723 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.44 (dd, *J* = 8.2, 1.9 Hz, 2 H), 7.14 (d, *J* = 8.2 Hz, 2 H), 4.16–4.03 (m, 4 H), 2.34 (d, *J* = 1.8 Hz, 3 H), 1.67–1.60 (m, 4 H), 1.35–1.22 (m, 12 H), 0.88 (t, *J* = 6.9 Hz, 6 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 139.1 (d, J_{C-P} = 3.2 Hz, 1 C), 134.5 (d, J_{C-P} = 5.1 Hz, 2 C), 130.1 (d, J_{C-P} = 2.2 Hz, 2 C), 122.9 (d, J_{C-P} = 7.2 Hz, 1 C), 68.0 (d, J_{C-P} = 6.6 Hz, 2 C), 31.3 (s, 2 C), 30.1 (d, J_{C-P} = 7.2 Hz, 2 C), 25.1 (s, 2 C), 22.5 (s, 2 C), 21.1 (s, 1 C), 13.9 (s, 2 C).

^{31}P NMR (162 MHz, $CDCl_3$): δ = 25.06.

MS (ESI): *m*/*z* = 373 $[M + H]^+$, 395 $[M + Na]^+$.

HRMS (ESI-TOF): *m*/*z* $[M + H]^+$ calcd for $C_{19}H_{33}O_3PS$: 373.1966; found: 373.1969.

O,*O*-Dihexyl *Se*-Phenyl Phosphoroselenoate (4g)

Pale yellow oil.

IR (film): 3059, 2956, 2930, 2859, 1578, 1477, 1439, 1380, 1253, 1091, 1039, 991, 855, 789, 739 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.66–7.63 (m, 2 H), 7.37–7.28 (m, 3 H), 4.17–4.03 (m, 4 H), 1.67–1.60 (m, 4 H), 1.34–1.22 (m, 12 H), 0.88 (t, *J* = 6.9 Hz, 6 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 135.5 (d, J_{C-P} = 4.7 Hz, 2 C), 129.4 (d, J_{C-P} = 1.9 Hz, 2 C), 128.7 (d, J_{C-P} = 2.3 Hz, 1 C), 123.9 (d, J_{C-P} = 8.3 Hz, 1 C), 67.9 (d, J_{C-P} = 6.4 Hz, 2 C), 31.3 (s, 2 C), 30.0 (d, J_{C-P} = 7.2 Hz, 2 C), 25.1 (s, 2 C), 22.5 (s, 2 C), 13.9 (s, 2 C).

^{31}P NMR (162 MHz, $CDCl_3$): δ = 19.69 [s (isotopes 76, 78, 80, 82) and d (isotope 77), $^1J_{P-Se}$ = 479.8 Hz].

MS (ESI): *m*/*z* = 407 $[M + H]^+$, 429 $[M + Na]^+$.

HRMS (ESI-TOF): *m*/*z* $[M + H]^+$ calcd for $C_{18}H_{31}O_3PSe$: 407.1255; found: 407.1262.

_O_,_O_-Dihexyl _Se_-4-Tolyl Phosphoroselenoate (4h)

Pale yellow oil.

IR (film): 3021, 2956, 2929, 2859, 1489, 1467, 1380, 1253, 1117, 1039, 991, 854, 803, 722 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.53–7.50 (m, 2 H), 7.11 (d, *J* = 8.1 Hz, 2 H), 4.16–4.02 (m, 4 H), 2.33 (d, *J* = 1.5 Hz, 3 H), 1.67–1.60 (m, 4 H), 1.34–1.22 (m, 12 H), 0.88 (t, *J* = 6.9 Hz, 6 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 138.9 (d, J_{C-P} = 2.8 Hz, 1 C), 135.5 (d, J_{C-P} = 4.5 Hz, 2 C), 130.2 (d, J_{C-P} = 2.1 Hz, 2 C), 120.0 (d, J_{C-P} = 8.4 Hz, 1 C), 67.8 (d, J_{C-P} = 6.4 Hz, 2 C), 31.3 (s, 2 C), 30.0 (d, J_{C-P} = 7.2 Hz, 2 C), 25.1 (s, 2 C), 22.5 (s, 2 C), 21.1 (s, 1 C), 13.9 (s, 2 C).

^{31}P NMR (162 MHz, $CDCl_3$): δ = 20.01 [s (isotopes 76, 78, 80, 82) and d (isotope 77), $^1J_{P-Se}$ = 486.4 Hz].

MS (ESI): *m*/*z* = 421 $[M + H]^+$, 443 $[M + Na]^+$.

HRMS (ESI-TOF): *m*/*z* $[M + H]^+$ calcd for $C_{19}H_{33}O_3PSe$: 421.1412; found: 421.1419.

_Se_-4-Chlorophenyl _O_,_O_-Dihexyl Phosphoroselenoate (4i)

Pale yellow oil.

IR (film): 3063, 2956, 2930, 2859, 1474, 1388, 1254, 1090, 1038, 1010, 991, 815, 788, 729 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.59–7.55 (m, 2 H), 7.29–7.26 (m, 2 H), 4.17–4.03 (m, 4 H), 1.68–1.61 (m, 4 H), 1.35–1.22 (m, 12 H), 0.88 (t, *J* = 6.8 Hz, 6 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 136.7 (d, J_{C-P} = 4.8 Hz, 2 C), 135.2 (d, J_{C-P} = 2.8 Hz, 1 C), 129.6 (d, J_{C-P} = 1.7 Hz, 2 C), 122.0 (d, J_{C-P} = 8.3 Hz, 1 C), 68.0 (d, J_{C-P} = 6.6 Hz, 2 C), 31.2 (s, 2 C), 30.0 (d, J_{C-P} = 7.2 Hz, 2 C), 25.1 (s, 2 C), 22.5 (s, 2 C), 13.9 (s, 2 C).

^{31}P NMR (162 MHz, $CDCl_3$): δ = 18.95 [s (isotopes 76, 78, 80, 82) and d (isotope 77), $^1J_{P-Se}$ = 473.0 Hz].

MS (ESI): *m*/*z* = 441 $[M + H]^+$, 463 $[M + Na]^+$.

HRMS (ESI-TOF): *m*/*z* $[M + H]^+$ calcd for $C_{18}H_{30}ClO_3PSe$: 441.0913; found: 441.0920.

_O_,_O_-Diethyl _Te_-4-Tolyl Phosphorotelluroate (5d)

Pale yellow oil.

IR (film): 2981, 2926, 2867, 1486, 1442, 1391, 1240, 1160, 1011, 962, 799, 758 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.72 (dd, *J* = 8.0, 1.6 Hz, 2 H), 7.07 (d, *J* = 2.0 Hz, 2 H), 4.20–4.08 (m, 4 H), 2.34 (d, *J* = 0.9 Hz, 3 H), 1.32 (t, *J* = 7.1 Hz, 6 H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 140.1 (d, J_{C-P} = 3.9 Hz, 2 C), 139.1 (d, J_{C-P} = 2.7 Hz, 1 C), 130.6 (d, J_{C-P} = 2.0 Hz, 2 C), 104.7 (d, J_{C-P} = 8.0 Hz, 1 C), 63.4 (d, J_{C-P} = 5.3 Hz, 2 C), 21.3 (s, 1 C), 15.7 (d, J_{C-P} = 7.4 Hz, 2 C).

^{31}P NMR (162 MHz, $CDCl_3$): δ = –0.49 [s (isotopes 122, 124, 126, 128, 130) and d (isotope 125), $^1J_{P-Te}$ = 1356.7 Hz].

MS (ESI): *m*/*z* = 359 $[M + H]^+$, 381 $[M + Na]^+$.

HRMS (ESI-TOF): *m*/*z* $[M + H]^+$ calcd for $C_{11}H_{17}O_3PTe$: 359.0056; found: 359.0059.

***O*-Isopropyl *O*-(2′,3′-*O*,*O*-Isopropylideneuridinyl) *S*-Phenyl Phosphorothioate (10)**

Colorless oil. Many ^{1}H and ^{13}C NMR signals were split due to the presence of (phosphate) diastereoisomers in the sample.

IR (film): 3183, 3062, 2985, 2938, 2821, 1694, 1632, 1582, 1455, 1418, 1380, 1261, 1158, 1069, 989, 860, 750 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 9.02 (br s, 1 H, NH), 7.60–7.55 (m, 2 H, H_{arom}), 7.37–7.28 (m, 4 H, H6, 3 H_{arom}), 5.86 and 5.81 (2 d, *J* = 1.8, 2.6 Hz, 1 H, H1′), 5.65–5.60 (m, 1 H, H5), 4.88–4.80 (m, 1 H, C*H*Me_2), 4.75–4.66 (m, 2 H, H2′, H3′), 4.40–4.25 (m, 3 H, H4′, H5′), 1.57 and 1.56 [2 s, 3 H, =C$(CH_3)_2$], 1.37–1.26 (m, 9 H, CH_3).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 162.95 (C4), 149.97, 149.94 (C2), 141.23, 141.18 (C6), 134.66, 134.61, 134.47, 134.41 (CH_{arom}), 129.46, 129.43, 129.41 (CH_{arom}), 129.31, 129.28, 129.22, 129.20 (CH_{arom}), 126.06, 126.02, 125.99, 125.95 (C_{arom}), 114.67, 114.62 (=*C*Me_2), 102.70, 102.68 (C5), 93.11, 92.72 (C1′), 84.91, 84.82, 84.68, 84.60 (C4′), 84.42, 84.28 (C2′), 80.41, 80.38 (C3′), 74.35, 74.31, 74.29, 74.24 (*C*HMe_2), 66.74, 66.68 (C5′), 27.11, 27.09 [=C$(CH_3)_2$], 25.24 [=C$(CH_3)_2$], 23.94, 23.91, 23.88 [CH$(CH_3)_2$], 23.51, 23.45 [CH$(CH_3)_2$].

^{31}P NMR (162 MHz, $CDCl_3$): δ = 22.83, 22.75.

MS (ESI): *m*/*z* = 499 $[M + H]^+$, 521 $[M + Na]^+$.

HRMS (ESI-TOF): *m*/*z* $[M + H]^+$ calcd for $C_{21}H_{27}N_2O_8PS$: 499.1304; found: 499.1310.

***O*-Isopropyl *O*-(2′,3′-*O*,*O*-Isopropylideneuridinyl) *Se*-Phenyl Phosphorothioate (11)**

Pale yellow oil. Many ^{1}H and ^{13}C NMR signals were split due to the presence of (phosphate) diastereoisomers in the sample.

IR (film): 3185, 3060, 2984, 2937, 2821, 1694, 1632, 1578, 1455, 1419, 1380, 1158, 1069, 983, 860, 812, 741 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 9.18 (br s, 1 H, NH), 7.65–7.62 (m, 2 H, H_{arom}), 7.36–7.27 (m, 4 H, H6, 3 H_{arom}), 5.87 and 5.80 (2d, *J* = 2.0, 2.5 Hz, 1 H, H1′), 5.65 and 5.58 (2 dd, *J* = 8.1, 1.7, 8.1, 1.8 Hz, 1 H, H5), 4.90–4.81 (m, 1 H, C*H*Me_2), 4.77–4.63 (m, 2 H, H2′, H3′), 4.39–4.24 (m, 3 H, H4′, H5′), 1.57 and 1.56 [2 s, 3 H, =C$(CH_3)_2$], 1.37–1.28 (m, 9 H, CH_3).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 163.08, 163.05 (C4), 150.02, 149.99 (C2), 141.29, 141.14 (C6), 135.67, 135.63, 135.36, 135.31 (CH_{arom}), 129.60, 129.58 (CH_{arom}), 129.11, 129.09, 128.98, 128.96 (CH_{arom}), 123.50, 123.42, 123.33, 123.25 (C_{arom}), 114.62, 114.56 (=*C*Me_2), 102.68, 102.63 (C5), 93.21, 92.64 (C1′), 84.91, 84.82, 84.60, 84.52 (C4′), 84.47, 84.31 (C2′), 80.47, 80.42 (C3′), 74.12, 74.08, 74.06, 74.02 (*C*HMe_2), 66.49, 66.45, 66.39 (C5′), 27.11, 27.08 [=C$(CH_3)_2$], 25.25 [=C$(CH_3)_2$], 23.95, 23.92, 23.89 [C$(CH_3)_2$], 23.51, 23.49, 23.44 [C$(CH_3)_2$].

^{31}P NMR (162 MHz, $CDCl_3$): δ = 17.63, 17.46 [s (isotopes 76, 78, 80, 82) and d (isotope 77), $^1J_{P-Se}$ = 493.5, 496.9 Hz].

MS (ESI): *m*/*z* = 547 $[M + H]^+$, 569 $[M + Na]^+$.

HRMS (ESI-TOF): *m*/*z* $[M + H]^+$ calcd for $C_{21}H_{27}N_2O_8PSe$: 547.0750; found: 547.0755.

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