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Synthesis of Dihydrothiophene, Thiophene, and Their Selenium Analogues Carrying Four Phosphoryl Groups

Shigeru Sasaki,* Kazutaka Adachi, and Masaaki Yoshifuji

Department of Chemistry, Graduate School of Science, Tohoku University,
Aoba, Sendai 980-8578, Japan

sasaki@mail.tains.tohoku.ac.jp

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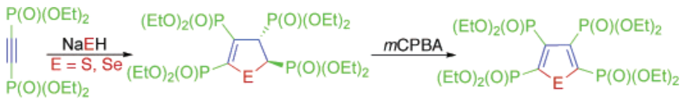
ABSTRACT



Sodium hydrosulfide undergoes addition to two molecules of bis(diethoxyphosphoryl)acetylene followed by cyclization to give a 2,3-dihydrothiophene carrying four phosphoryl groups. Oxidation of the 2,3-dihydrothiophene with *m*CPBA gives the corresponding sulfoxide or sulfone depending on the ratio of the reagents, and the sulfoxide is dehydrated to afford a tetraphosphorylthiophene. The corresponding dihydroselenophene and selenophene are also synthesized in a similar manner.

Cyclic π-conjugated systems fully substituted by heteroatoms have attracted considerable attention. There are a large number of such systems consisting of benzene derivatives carrying six nitrogen, oxygen, sulfur, and silicon functional groups. However, there are limited examples of cyclic π-conjugated systems substituted with phosphorus groups. Although a cyclopentadienyl ligand with five phosphorus substituents has been synthesized recently,[1] the introduction of the phosphorus substituents onto a benzene ring is still limited to four substituents.[2] On the other hand, phosphoryl acetylenes have been reported as convenient synthetic intermediates or building blocks for phosphoryl compounds and can undergo various reactions such as [2 + 2], [3 + 2], and [4 + 2] cycloadditions,[3] conjugate additions,[3] and metallacycle formation.[4] Recently, we have been involved in constructing cyclic π-conjugated systems substituted with phosphorus functional groups, and we have employed diphosphorylacetylenes for the synthesis of the η^4-(tetraphosphorylcyclobutadiene)cobalt complexes, which work as bisbidentate ligands to form a one-dimensional coordination polymer.[5] However, the attempted preparation of five-membered aromatic heterocycles by way of metallacycle intermediates such as the zircona-[6] and titanacycles[7] from bis(diethoxyphosphoryl)acetylene (**1**)[8] was unsuccessful, and we shifted our focus to direct addition of typical-element nucleophiles to **1**. Herein, we report the reaction of **1** with sodium hydrosulfide, which has been found to undergo addition to two molecules of **1**, followed by cyclization to

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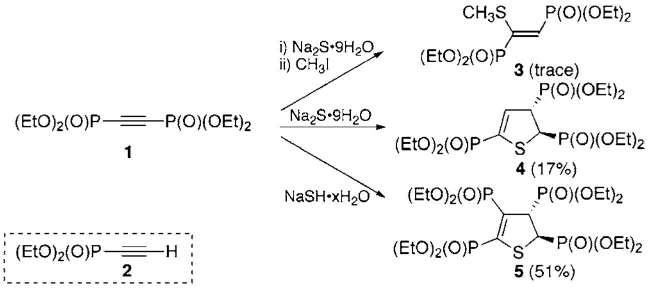
give a 2,3-dihydrothiophene carrying four phosphoryl groups. Oxidation of the 2,3-dihydrotetraphosphorylthiophene with *m*CPBA affords a thiophene carrying four phosphoryl groups. The corresponding selenium compounds are obtained in a similar manner. The structures of the newly synthesized tetraphosphorylheterocycles are discussed.

Reaction of sodium arylsulfides with **1** was reported to give a 1-arylthio-2-phosphorylethylene resulting from addition of the arylsulfide to diethoxyphosphorylacetylene (**2**), which was generated in situ by nucleophilic attack of sodium arylsulfide on the phosphorus atom of **1**.[9]

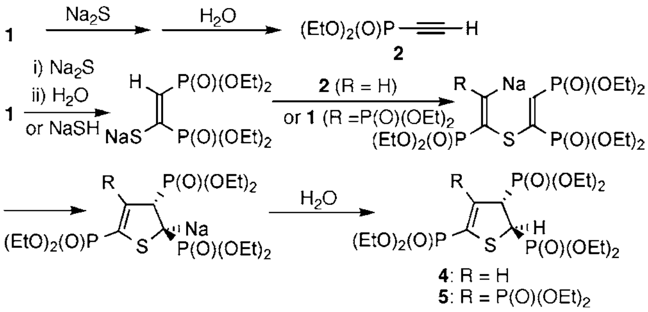
Our attempt to synthesize 1-methylthio-1,2-bis(diethoxyphosphoryl)ethene (**3**) by reaction of 1 equiv of sodium sulfide with **1** in tetrahydrofuran followed by quenching with iodomethane gave only a trace amount of **3**. However, detailed examination of reaction conditions revealed that reaction of 0.5 equiv of sodium sulfide with **1** in ether gives 2,3-dihydro-2,3,5-triphosphorylthiophene **4** and a trace amount of 2,3-dihydro-2,3,4,5-tetraphosphorylthiophene **5** (Scheme 1).

Scheme 1. Synthesis of Tri- and Tetraphosphoryldihydrothiophenes



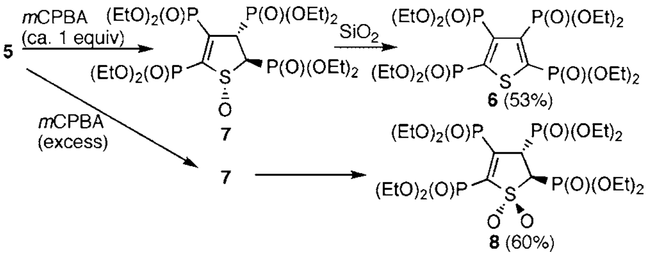
The formation of **4** can be rationalized by addition of sodium sulfide to **1** followed by the second addition to in situ generated **2** and further intramolecular addition of the resulting carbanion to the alkene (Scheme 2). Therefore, sodium hydrosulfide, which is expected to be less nucleophilic, was employed to suppress formation of **2** and was allowed to react with a more than 2-fold excess of **1** to give **5** as expected. Formation of the five-membered rings **4** and **5** with *trans* configuration of the phosphoryl groups at the 2 and 3 positions can be explained by *cis* addition of the sulfide to the alkynes and alkenes. Sodium sulfide was reported to undergo kinetically favored *cis* addition to the phosphorylalkynes, and the resulting olefins isomerize to thermodynamically stable *trans* forms.[9]

Scheme 2. Formation of Dihydrothiophene



Attempted aromatization of **5** with *o*- or *p*-chloranil or DDQ in refluxing toluene or 1,4-dioxane resulted in recovery of **5**; however, oxidation of **5** with *m*CPBA unexpectedly afforded 2,3,4,5-tetraphosphorylthiophene **6** (Scheme 3).

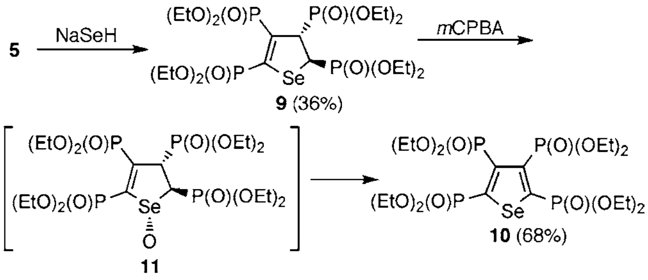
Scheme 3. Synthesis of Tetraphosphorylthiophene



Oxidation of **5** with *m*CPBA gave sulfoxide **7** as an initial product. Sulfoxide **7** was obtained as a single isomer, and the configuration was assigned as shown in Scheme 3 assuming oxidation from less hindered side. Sulfoxide **7** was gradually oxidized to sulfone **8** in the presence of excess *m*CPBA. Although **7** was stable without excess *m*CPBA, attempted chromatographic purification over SiO_2 led to dehydration to give thiophene **6**. Thiophene **6** resisted further oxidation by *m*CPBA and was stable at 120 °C in *o*-dichlorobenzene. Similar oxidation resistance by introduction of phosphoryl groups was observed in tetraphosphorylcyclobutadiene complexes.[5]

Sodium hydroselenide similarly added to **1** to give 2,3-dihydrotetraphosphorylselenophene **9** and following oxidation with *m*CPBA afforded tetraphosphorylselenophene **10** (Scheme 4). Formation of selenophene **10** can be explained by oxidation of **9** to the corresponding selenoxide **11** followed by dehydration similarly to the sulfur derivatives; however, the corresponding selenoxide **11** did not allow us

Scheme 4. Synthesis of Tetraphosphorylselenophene



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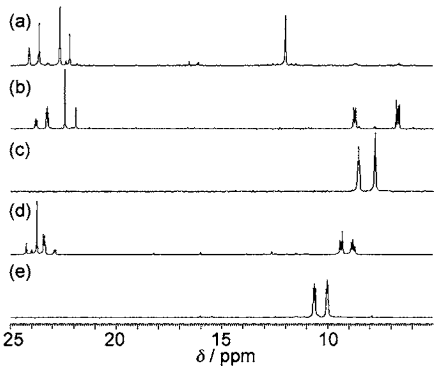

Figure 1. ^{31}P NMR (162 MHz, CDCl$_3$) of (a) **4**, (b) **5**, (c) **6**, (d) **9**, and (e) **10**.

characterization and readily gave **10** in the reaction mixture. Excess *m*CPBA did not give the corresponding selenone or selenophene oxides but rather **10** in reduced yield.

The structures of the phosphorus-substituted ring systems are clearly reflected on the ^{31}P, ^{13}C, and ^{77}Se NMR spectra. The ^{31}P NMR signals of dihydrothiophenes **4** and **5** and dihydroselenophene **9** consist of an AB pattern at δ 22−24 ppm corresponding to the phosphoryl groups attached to the alkane carbons and a singlet (**4**) or multiplets (**5**, **9**) at δ 6−12 ppm corresponding to those attached to the alkene carbons (Figure 1, Table 1). Large coupling constants (73−85 Hz) of the AB patterns indicate *trans* configuration of the phosphoryl groups attached to the alkane carbons.[10] Lack of detectable small couplings in **4** is consistent with the absence of a phosphoryl group on the 4-carbon. Sulfoxide **7** and sulfone **8** also exhibit phosphoryl groups attached to the alkane carbons in lower field and those attached to the alkene carbons in higher field. Coupling constants between the 2- and 3-phosphorus (38−42 Hz) become smaller than those of **5** probably because of conformational change resulting from oxidation on the sulfur. Thiophene **6** and selenophene **10** display two ^{31}P NMR signals as pseudo triplets resulting from the unresolved AA′XX′ pattern at δ 7−11 ppm. Introduction of the four phosphoryl groups leads to an upfield shift of the phosphoryl groups as compared with mono-[11] and diphosphorylthiophenes.[12]

Table 1. ^{31}P NMR (162 MHz, CDCl$_3$) Chemical Shifts of Tetraphosphoryl Heterocycles and Related Compounds

	2,3-P (δ/ppm)		4,5-P (δ/ppm)	
4	22.5	23.9		12.0
5	22.2	23.5	8.7	6.7
6	8.5	7.7	7.7	8.5
7	20.1	18.8	7.1	5.9
8	14.2	19.3	1.3	7.2
9	23.9	23.3	8.7	9.3
10	10.6	10.0	10.0	10.6

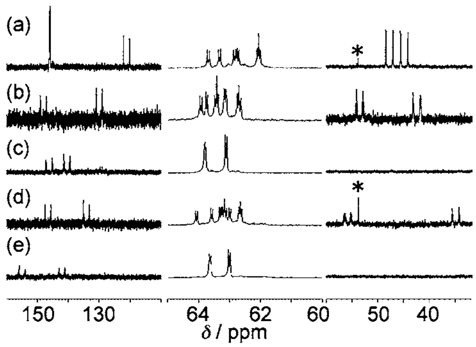

Figure 2. ^{13}C NMR (101 MHz, CDCl$_3$) of (a) **4**, (b) **5**, (c) **6**, (d) **9**, and (e) **10**. $*$ denotes impurity.

The ^{13}C NMR signals of the alkene carbons of dihydrothiophenes **4** and **5**, dihydrothiophene *S*-oxides **7** and **8**, and dihydroselenophene **9** carrying the phosphoryl groups are observed at δ 120−153 ppm with large $^1J_{\mathrm{CP}}$ (173−197 Hz) and small couplings, whereas only small coupling constants with ^{31}P nuclei are observed for the 4-carbon of **4** at δ 146.4 ppm (Figure 2, Table 2). Peaks assigned to the two alkane carbons of **4**, **5**, **7**, **8**, and **9** carrying the phosphoryl groups are observed around δ 35−61 ppm and are also accompanied by a large $^1J_{\mathrm{CP}}$ coupling constant (119−144 Hz). Thiophene **6** and selenophene **10** do not show any signals in this region. Dihydrothiophenes **4** and **5**, dihydrothiophene *S*-oxides **7** and **8**, and dihydroselenophene **9** show six or eight doublets ($^2J_{\mathrm{CP}}$ = ca. 6 Hz) at δ 62−65 ppm corresponding to nonequivalent methylene carbons, reflecting an unsymmetrical environment arising from the two chiral carbons in the five-membered ring. On the other

Table 2. ^{13}C NMR (101 MHz, CDCl$_3$) Chemical Shifts of Tetraphosphoryl Heterocycles and Related Compounds

	2,3-C (δ/ppm)		4,5-C (δ/ppm)	
4	45.3	48.2	146.4	121.7
5	42.9	53.9	148.5	130.4
6	146.1	140.4	140.4	146.1
7	53.9	60.7	152.9	149.8
8	43.6	59.0	147.5	145.1
9	35.4	56.3	147.0	134.7
10	155.4	142.5	142.5	155.4
thiophene[a]	125.6	127.3	127.3	125.6
12[b]	135.94	136.86	136.86	135.94
selenophene[a]	131.0	128.8	128.8	131.0
13[c]	142.49	139.25	139.25	142.49

[a] Reference 13. [b] Reference 14. [c] Reference 15.

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hand, those of thiophene **6** and selenophene **10** appear as only two groups of signals. Introduction of the four phosphoryl groups into the thio- and selenophene framework leads to a downfield shift and nonequivalence of aromatic carbons (**6**: δ 140.4, 146.1 ppm. **10**: δ 142.5, 155.4 ppm) especially for **10** as compared with the parent thiophene (δ 125.6, 127.3 ppm),[13] selenophene (δ 131.0, 128.8 ppm),[13] tetramethyl thiophenetetracarboxylate (**12**) (δ 135.94, 136.86 ppm),[14] and tetramethyl selenophenetetracarboxylate (**13**) (δ 139.25, 142.49 ppm).[15]

^{77}Se NMR signal of **9** appears at δ 555.2 ppm with coupling by one ^{31}P ($^{2}J_{\mathrm{SeP}} = 48.3$ Hz) and one ^{1}H ($^{2}J_{\mathrm{SeH}} = 21.2$ Hz) nuclei (Figure 3). The chemical shift lies in a lower region for dihydroselenophene (δ 380−580 ppm),[16] and the coupling pattern is consistent with an unsymmetrical structure. Selenophene **10** exhibits a ^{77}Se NMR signal as a triplet ($^{2}J_{\mathrm{SeP}} = 49.9$ Hz) at δ 929.5 ppm. The chemical shift is the lowest among known selenophenes (δ 605 (selenophene),[17] 699 (**13**)[15] ppm) and is rather close to those of selenophene oxides (δ 900−1000 ppm)[18] and dioxides (δ 1000−1100 ppm),[19] whereas the coupling pattern agrees with the symmetrical structure of **10**. Because other spectroscopic evidence as well as the reaction mechanism and reactivity unambiguously support formation of selenophene **10** rather than the *Se*-oxides, the significant downfield shift of ^{77}Se as well as the ^{13}C chemical shifts of the five-membered ring is attributed to the interaction of the four phosphoryl groups with the aromatic system. Small differences in P═O stretching and $^{2}J_{\mathrm{SeP}}$ between **9** and **10** exclude strong enhancement of direct interaction of the phosphoryl groups and the selenium atom in **10**.

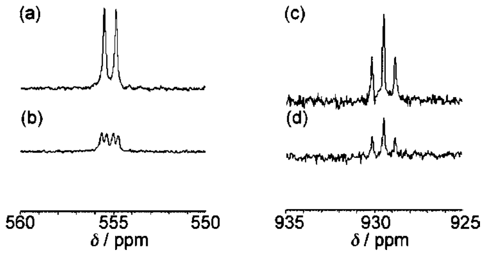

Figure 3. ^{77}Se NMR (76.3 MHz, CDCl$_3$) of (a) **9**, (b) **9** (non ^{1}H-decoupled), (c) **10**, and (d) **10** (non ^{1}H-decoupled).

Phosphonates **3**−**10** display a strong IR band around 1250 (ν(P═O)) and 1020 (ν(POC)) cm^{-1}. Oxidation of the dihydro derivatives to the thiophene and selenophene has little effect on 600−1500 cm^{-1} of the IR spectra excluding formation of thiophene *S*-oxides or selenophene *Se*-oxides, which have a characteristic band in this area.[18,19] Sulfone **8** exhibits a characteristic band at 1335 cm^{-1} (ν(SO$_2$)).

Formation of the tetraphosphorylthiophene and selenophene from the corresponding dihydro derivatives is also reflected on the UV−vis spectra. Thiophene **6** and selenophene **10** show red shift (18 nm) as compared with thiophene and selenophene ($\lambda_{\max}$ (methanol) = 248 (**6**), 268 (**10**), 230 (thiophene),[20] 250 (selenophene)[17] nm), whereas dihydro derivatives **5** and **9**, which can be regarded as push−pull substituted alkenes, exhibit two maximum peaks in longer wavelength than **6** and **10** as well as the parent compound ($\lambda_{\max}$ (methanol) = 304, 265 (**5**), 321, 275 (**9**), 205 (dihydrothiophene)[20] nm).

In conclusion, we have revealed the unique reactivity of diphosphorylacetylene **1** with sodium hydrosulfide and hydroselenide to form dihydrothiophene **5** and dihydroselenophene **9** and have synthesized the first thiophene and selenophene carrying four phosphoryl groups. Investigation into the reactivity of these phosphorus-substituted heterocycles and applications to the building blocks of functional materials is in progress.

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Supporting Information Available: Experimental procedures, characterization, and ^{1}H, ^{13}C, and ^{31}P NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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