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PII: S0040-4020(17)30406-4

DOI: 10.1016/j.tet.2017.04.035

Reference: TET 28636

To appear in: *Tetrahedron*

Received Date: 19 February 2017

Revised Date: 12 April 2017

Accepted Date: 13 April 2017

Please cite this article as: He W, Hou X, Li X, Song L, Yu Q, Wang Z, Synthesis of P(O)-S organophosphorus compounds by dehydrogenative coupling reaction of P(O)H compounds with aryl thiols in the presence of base and air, *Tetrahedron* (2017), doi: 10.1016/j.tet.2017.04.035.

Graphical Abstract

Synthesis of P(O)-S organophosphorus compounds by dehydrogenative coupling reaction of P(O)H compounds with aryl thiols in the presence of base and air

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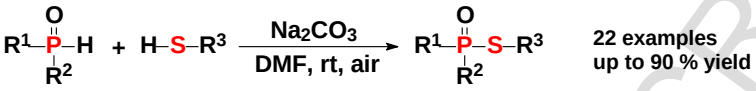

R^1= phenyl, aryl, alkoxyl; R^2= phenyl, aryl, alkoxyl; R^3= aryl

- ⋆ Metal-free
- ⋆ Mild reaction conditions
- ⋆ Operational simplicity
- ⋆ Broad substract scope
- ⋆ Under air atmosphere

Tetrahedron
journal homepage: www.elsevier.com

Synthesis of P(O)-S organophosphorus compounds by dehydrogenative coupling reaction of P(O)H compounds with aryl thiols in the presence of base and air

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ARTICLE INFO

Article history:
Received
Received in revised form
Accepted
Available online

Keywords:
Thiophosphate
Thiophosphonate
Diphenylphosphine oxide
Aryl thiols
Dehydrogenative coupling

ABSTRACT

The synthesis method of P(O)-S organophosphorus compounds by dehydrogenative coupling reaction of P(O)H compounds and aryl thiols was developed. The reaction was carried in the presence of a base and air, and exhibited good characters such as metal-free, mild reaction temperature, excellent substrate tolerance and with moderate to good yields. A plausible mechanism was proposed.

1. Introduction

Sulfur-containing organophosphorus compounds, such as thiophosphates and thiophosphonates, have attracted much attention in recent decades due to their widespread application in pharmaceuticals and agrochemicals.[1,2] Accordingly, study on the synthesis of these compounds is extensive. The reported methods for the synthesis of thiophosphates and thiophosphonates include Michaelis-Arbuzov reaction between $P(OR)_3$ and RSO_2Cl,[3] nucleophilic substitution of $R_2P(O)Cl$ with RSH,[4] coupling-reductive reactions between $R_2P(O)H$ and RSO_2Cl,[5] direct coupling reaction between $R_2P(O)H$ and RSH,[6] and others.[7]

Recently, the direct coupling reaction of H-phosphine oxides/H-phosphinate esters and thiols has got much attention because of the atom economic character. Lee *et al.* and Kaboudin *et al*. reported the reaction of H-phosphinate esters with thiol prompted by NCS,[8] CuI/Et_3N[9] and 1,3-Dichloro-5,5-dimethylhydantoin (DCDMH),[10] respectively. Pan *et al*. reported the reaction of H-phosphine oxides with thiols using tert-butyl peroxybenzoate (TBPB) and KI as additives.[11] While, Yang *et al*. mentioned the reaction of H-phosphine oxides with thiols prompted by catalytic $CuBr_2$ and 1.5 equiv. 2,3-Dichloro-5,6-dicyano-4-benzoquinone (DDQ).[12] In these reactions, metal catalyst or other reaction promoters were needed. Han et al. has reported the modification of the Atherton–Todd reaction of secondary phosphine oxide with thiols in chloroform by the aid of LiOBu-*t*.[13] But, the organophosphorus reactant is limited to secondary phosphine oxide and the promoters are limited to use of chloroform and LiOBu-*t*.

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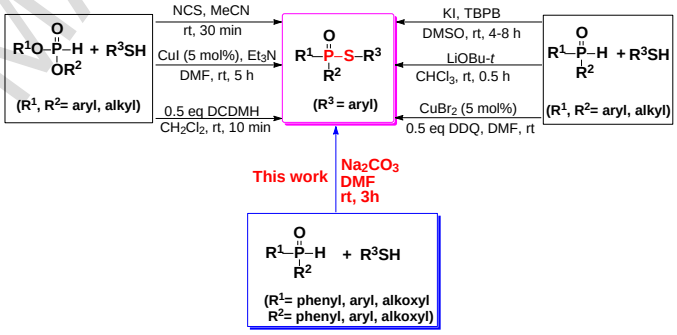


Scheme 1. **Synthesis of thiophosphates and thiophosphonates.**

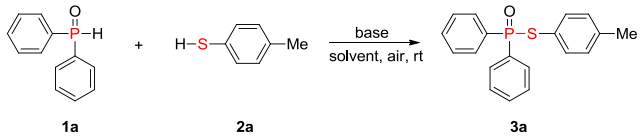
As we focused our attention on the environmental friendly synthesis of sulfur-containing organophosphorus compounds, we are interested to find that the direct dehydrogenative coupling reaction of H-phosphine oxide, H-phosphonate and H-phosphite with aryl thiol can readily proceed with the presence of base in varied solvents. Herein we report the investigation of this method.

2. Results and discussion

In the initial work, diphenylphosphine oxide (**1a**) and 4-methyl benzenethiol (**2a**) were used as model reactants to optimize the reaction conditions. It was found **1a** and **2a** can react under various conditions (Table 1). Firstly, the reaction was carried out in the presence of KOH in EtOH at room temperature. To our delight, the desired product (**3a**) was obtained in a yield

of 40% within 8 h (Table 1, entry 1). Encouraged by this result, we next surveyed a range of base under the same conditions (Table 1, entries 2-5). These results showed that Na_2CO_3 has a good effect, which afforded **3a** in 70% yield. When the dosage of **1a** was increased to 2.0 equiv, the product yield of **3a** was reduced to 48% unexpectedly (Table 1, entry 6). The effect of solvents was also investigated (Table 1, entries 7-13). It was found the proceeding of this reaction was greatly influenced by solvent. Only a trace amount of desired product can be detected when using CH_3OH as solvent (Table 1, entry 7). And other solvents, such as H_2O, CH_2Cl_2, CH_3CN and DMSO resulted in lower yields (Table 1, entries 8, 11, 12 and 13). However, when the reaction was carried in *n*-BuOH or DMF, the product **3a** were given in 84% or 87% yields, respectively (Table 1, entries 9 and 10). Since the reaction can be finished in relatively shorter time in DMF, DMF was selected as the optimal solvent.

Table 1. Optimization of reaction conditions[a]

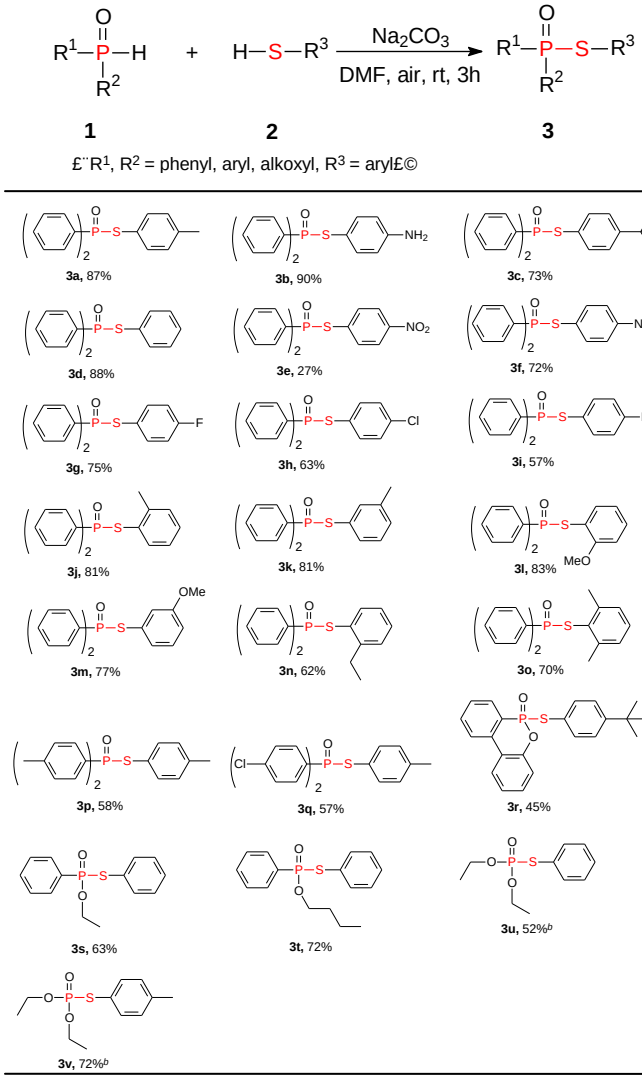


Entry	Base	Solvent	Yield[b](%)
1	KOH	CH_3CH_2OH	40
2	K_2CO_3	CH_3CH_2OH	44
3	$NaHCO_3$	CH_3CH_2OH	61
4	Na_2CO_3	CH_3CH_2OH	70
5	CH_3CH_2ONa	CH_3CH_2OH	34
6[c]	Na_2CO_3	CH_3CH_2OH	48
7	Na_2CO_3	CH_3OH	Trace
8	Na_2CO_3	H_2O	45
9[d]	Na_2CO_3	*n*-BuOH	84
10[e]	Na_2CO_3	DMF	87
11	Na_2CO_3	CH_2Cl_2	14
12	Na_2CO_3	CH_3CN	43
13	Na_2CO_3	DMSO	34

[a]Unless otherwise noted, the reactions were performed by adding **1a** (1.2 mmol), **2a** (1 mmol) and base (1.2 mmol) in solvent (5 ml) at room temperature for 8 h. [b]Isolated yields. [c]**1a** (2 mmol), **2**a (1 mmol). [d]Reactions were performed for 24 h. [e]Reactions were performed for 3 h.

Under the optimized reaction conditions, we then investigated the scope and limitations of the substrates of the reaction. As listed in Scheme 2, the investigated varied aryl thiols readily reacted with diphenylphosphine oxide to form thiophosphinates in moderate to good yields. Aryl thiols bearing electron-donating group at the *para*-position such as methyl, amino, and *tert*-butyl groups coupled with diphenylphosphine oxide to generate the expect products in good yields (Scheme 2, **3a**-**3c**). Thiophenol is also a viable substrate with 88% yield of target compound (Scheme 2, **3d**). The aryl thiol with strong electron-withdrawing group of $-NO_2$ leaded to lower yields of the desired product (Scheme 2, **3e**), while the other electron-withdrawing groups resulted in moderate yields of thiophosphinates (Scheme 2, **3f**-**3i**). The steric hindrance also affected the reaction between diphenylphosphine oxide and aryl thiols. To our delight, slightly lower but still good yields were obtained for the *meta*-substituted and *ortho*-substituted substrates (Scheme 2, **3j**-**3o**).

A series of P(O)H compounds were further examined to expand the synthesis utility of this method. Diarylphosphine oxides with methyl or Cl groups at *para*-position of the benzene ring performed with moderate yields (Scheme 2, **3p** and **3q**). Under the similar reaction conditions, 9,10-Dihydro-9-oxa-10-phosphaphenanthrene 10-oxide (DOPO) could also couple with 4-(*tert*-butyl)benzenethiol to furnish the corresponding product in 45% yield (Scheme 2, **3r**). In addition to secondary phosphine oxide, the coupling reaction between H-phosphinates or H-phosphonate with aryl thiols also proceeded well to provide the target compounds in moderate yields (Scheme 2, **3s**-**3v**).

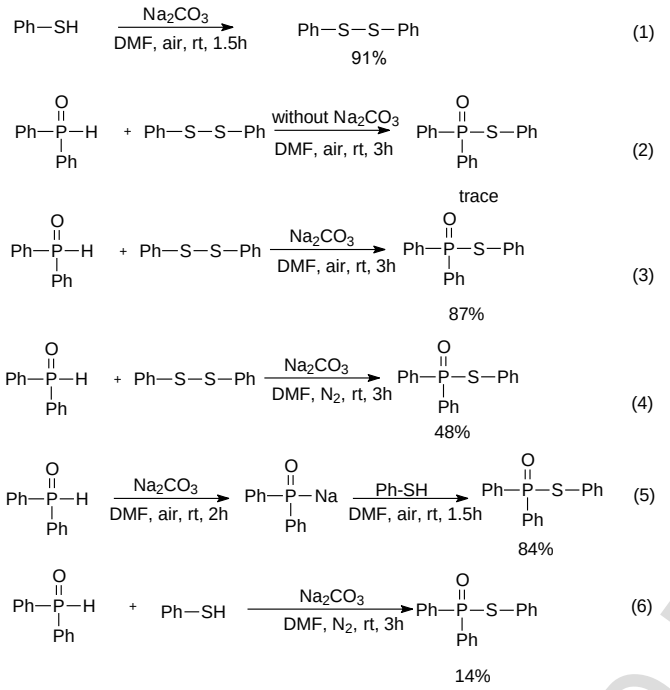


[a]Unless otherwise noted, the reactions were performed by adding P(O)H compounds (1.2 mmol), thiols (1 mmol) and DMF (10 ml) at room temperature for 3 h. Isolated yields. [b]Reactions were performed for 6 h.

Scheme 2. Reactions of P(O)H compounds with thiols[a]

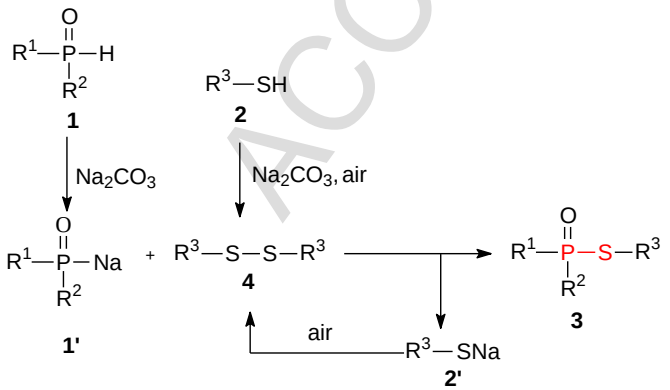
In order to understand the mechanism, controlled experiments were performed (Scheme 3). Phenyl disulfide (confirmed by NMR) with 91% yield was readily formed from **2d** in the present of both Na_2CO_3 and air (Scheme 3, eq 1). None of phenyl disulfide was formed when the reaction was carried without Na_2CO_3 in air or with Na_2CO_3 under N_2 atmosphere (Scheme 3, eq. 2, 3). Thus both Na_2CO_3 and the O_2 in the air played important roles in the formation of phenyl disulfide, and this similar phenomenon was also well reported by other literatures.[15] Under the standard conditions, **1a** and phenyl

disulfide reacted fairly well, and 87% yield of corresponding **3d** was generated (Scheme 3, eq 3). However, only traced amount of **3d** was found when the reaction of **1a** and PhSSPh was carried in air without Na_2CO_3. And when the reaction was carried with Na_2CO_3 under N_2 atmosphere, a yield of 48% was observed (Scheme 3, eq. 4). Since **1a** is an acid, it completed the react with Na_2CO_3 only in half an hour (traced by TLC, Scheme 3 eq.5). After addition of **2d** to the reaction mixture of **1a** and Na_2CO_3, normal yield of 84% target compound was get. But if the first step reaction of **1a** with Na_2CO_3 and the continue second step reaction with **2d** were performed under N_2, only 14% yield of **3d** was obtained (Scheme 3, eq 6).



Scheme 3. Mechanistic Experiments

Based on the previous reports[14-17] and our experiment results, a plausible reaction mechanism of the reaction between P(O)H compounds and aryl thiols in the presence of base was proposed (Scheme 4). Under the action of Na_2CO_3 and air, thiols **2** undergo homocoupling reaction to form disulfides **4**, in which Na_2CO_3 acted as a base and thus was critical and indispensable. At the same time, P(O)H compounds **1** reacts with Na_2CO_3 to give intermediate **1'**. The intermediate **1'** then reacts with disulfides **4** to afford compound **3** and **2'**. **2'** further converted to raw material of **2** with the presence of Na_2CO_3 and air, until the reaction completed.



Scheme 4. Proposed reaction mechanism

3. Conclutions

In summary, the sulfur-containing organophosphorus compounds synthesis method by coupling reaction of P(O)H compounds with aryl thiols was developed. The reaction can be carried out without the presence of metal catalysts at room temperature and air atmosphere, and afforded the products in moderate to good yields. The method exhibited a great functionality tolerance for the substrates. A plausible mechanism was proposed.[18]

4. Experimental section

4.1. General information

Reagents and solvents were purchased from commercial suppliers and used without additional purification. ^{1}H NMR, ^{31}P NMR and ^{13}C NMR spectra were recorded on a BrukerARX-400. FT-IR spectra were obtained with a Nicolet 380 spectrophotometer. Mass spectra were obtained on an Agilent LC-MS 1100 instrument. High resolution mass data were recorded on a Thermo Fisher Scientific LTQ FT Ultra instrument. Elemental analysis was performed with ElementerVario EL III instrument. Melting points were recorded on a SGW X-4 melting point apparatus and the thermometer is uncorrected.

4.2. Typical Procedure for the Preparation of 3a-3t.

P(O)H compounds 1 (1.2 mmol), thiols 2 (1.0 mmol), and Na_2CO_3 (1.2 mmol) were placed in a Schlenk tube. Then DMF (10 mL) was added. The reaction mixture was stirred at room temperature for 3 h. After the reaction was completed (monitored by TLC), H_2O (20.0 mL) was added, and the mixture was extracted by CH_2Cl_2 (3*10.0 mL). The combined organic layer was dried over anhydrous Na_2SO_4, filtered, and concentrated by rotary evaporation. The crude reaction mixture was purified by flash column chromatography on silica gel to afford the corresponding product.

4.2.1. **S-(4-methylphenyl) diphenylphosphinothioate (3a):** White solid (282 mg, 87 %). M.p.: 106-107 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.85 (dd, J_1 = 13.2 Hz, J_2 = 7.2 Hz, 4 H), 7.51-7.49 (m, 2H), 7.44-7.40 (m, 4H), 7.32 (d. *J*=6.8 Hz, 2H), 6.99 (d, *J*=7.6 Hz, 2H), 2.23 (s, 3H). ^{31}P NMR (162 MHz, $CDCl_3$): δ 41.2(s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ 21.2, 122.3 (d, *J* = 5.1 Hz), 128.5 (d, *J* = 13.1 Hz), 130.0 (d, *J* = 1.4 Hz), 131.7 (d, *J* = 10.2 Hz), 132.3 (d, *J* = 2.9 Hz), 132.7 (d, *J* = 105.8 Hz), 135.4 (d, *J* = 3.6 Hz), 139.2 (d, *J* = 2.9 Hz). MS (ESI, m/z): 324.9 $(M+H)^+$.

4.2.2. **S-(4-aminophenyl) diphenylphosphinothioate (3b):** White solid (290 mg, 90 %). M.p.: 163-165 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.86-7.82 (m, 4 H), 7.52-7.48 (m, 2H), 7.45-7.41 (m, 4H), 7.17-7.15 (m, 2H), 6.48-6.46 (m, 2H), 3.74 (br, 2H). ^{31}P NMR (162 MHz, $CDCl_3$): δ 41.1(s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ112.3 (d, *J* = 4.6 Hz), 115.6, 128.5 (d, *J* = 10.1 Hz), 131.7 (d, *J* = 8.2 Hz), 132.1 (d, *J* = 2.8 Hz), 132.9 (d, *J* = 83.6 Hz), 137.0 (d, *J* = 2.7 Hz), 147.6 (d, *J* = 1.8 Hz).

4.2.3. **S-(4-(tert-butyl)phenyl) diphenylphosphinothioate (3c):** White solid (266 mg, 73 %). M.p.: 118-119 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.86-7.82 (m, 4 H), 7.53-7.49 (m, 2H), 7.46-7.42 (m, 4H), 7.36-7.34 (m, 2H), 7.22-7.21 (m, 2H), 1.24 (s, 9H). ^{31}P NMR (162 MHz, $CDCl_3$): δ 41.5(s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ31.1, 34.6, 122.3 (d, *J* = 4.6 Hz), 126.3 (d, *J* = 1.9 Hz), 128.5 (d, *J* = 11.0 Hz), 131.7 (d, *J* = 8.3 Hz), 132.2 (d, *J* = 1.8

Hz), 132.8 (d, *J* = 85.5 Hz), 135.2 (d, *J* = 2.8 Hz), 152.3 (d, *J* = 1.8 Hz).

4.2.4. **S-phenyl diphenylphosphinothioate (3d):** White solid (271 mg, 88 %). M.p.: 84-86 °C. IR (KBr):1203, 1108, 746, 560 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 7.85 (dd, J_1 = 13.2 Hz, J_2 = 8.0 Hz, 4H), 7.53-7.49 (m, 2H), 7.46-7.42 (m, 6H), 7.26-7.18 (m. 3H). ^{31}P NMR (162 MHz, $CDCl_3$): δ 41.3 (s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ 126.3 (d, *J* = 5.1 Hz), 128.5 (d, *J* = 13.1 Hz), 128.9 (d, *J* = 1.4 Hz), 129.1 (d, *J* = 1.4 Hz), 131.6 (d, *J* = 10.2 Hz), 132.3 (d, *J* = 2.9 Hz), 132.6 (d, *J* = 106.5 Hz), 135.4 (d, *J* = 3.6 Hz). MS (ESI, m/z): 311.0 $(M+H)^+$. Anal. calcd. For $C_{18}H_{15}OPS$(%): C,69.66; H, 4.87. Found: C, 69.95; H, 5.01.

4.2.5. **S-(4-nitrophenyl) diphenylphosphinothioate (3e):** Yellow solid (96 mg, 27 %). M.p.: 105-107 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 8.04 (d, *J* = 8.8 Hz, 2H), 7.86 (dd, J_1 = 12.8 Hz, J_2 = 6.8 Hz, 4H), 7.68 (d, *J* = 8.4 Hz, 2H), 7.58-7.54 (m, 2H), 7.50-7.46 (m, 4H). ^{31}P NMR (162 MHz, $CDCl_3$): δ 41.9 (s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ 123.9, 128.9 (d, *J* = 13.2 Hz), 131.6 (d, *J* = 10.9 Hz), 131.8 (d, *J* = 107.2 Hz), 132.9 (d, *J* = 2.9 Hz), 135.1 (d, *J* = 4.4 Hz), 136.1 (d, *J* = 4.4 Hz), 147.9 (d, *J* = 2.2 Hz).

4.2.6. **S-(4-acetamidophenyl) diphenylphosphinothioate (3f):** White solid (263 mg, 72 %). M.p.: 146-147 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 9.66 (br, 1H), 7.86-7.81 (m, 4H), 7.56-7.54 (m, 2H), 7.50-7.43 (m, 6H), 7.22 (d, *J* = 8.4 Hz, 2H), 2.1 (s, 3H). ^{31}P NMR (162 MHz, $CDCl_3$): δ 42.6 (s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ 24.5, 118.1 (d, *J* = 5.8 Hz), 120.3, 128.8 (d, *J* = 13.1 Hz), 131.5 (d, *J* = 10.2 Hz), 132.2 (d, *J* = 106.4 Hz), 132.6 (d, *J* = 2.1 Hz), 136.4 (d, *J* = 2.9 Hz), 140.4, 169.4.

4.2.7. **S-(4-fluorophenyl) diphenylphosphinothioate (3g):** White solid (245 mg, 75 %). M.p.: 94-96 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 7.85 (dd, J_1 = 13.2 Hz, J_2 = 7.6 Hz, 4H), 7.52-7.48 (m, 2H), 7.45-7.43 (m, 6H), 6.89 (t, *J* = 8.0 Hz, 2H). ^{31}P NMR (162 MHz, $CDCl_3$): δ 41.4(d, *J* = 3.9 Hz, 1P). ^{19}F NMR (376 MHz, $CDCl_3$): δ -111.6 (d, *J* = 5.6 Hz, 1F). ^{13}C NMR (100 MHz, $CDCl_3$): δ 116.3 (dd, J_1 = 21.9 Hz, J_2 = 1.4 Hz), 121.2 (t, *J* = 4.3 Hz), 128.6 (d, *J* = 13.2 Hz), 131.6 (d, *J* = 10.2 Hz), 132.3 (d, *J* = 106.4 Hz), 132.5 (d, *J* = 3.0 Hz), 137.4 (dd, J_1 = 8.8 Hz, J_2 = 3.7 Hz), 163.4 (dd, J_1 = 248.7 Hz, J_2 = 2.2 Hz).

4.2.8. **S-(4-chlorophenyl) diphenylphosphinothioate (3h):** White solid (210 mg, 63 %). M.p.: 104-105 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 7.87-7.81 (m, 4H), 7.55-7.51 (m, 2H), 7.48-7.43 (m, 4H), 7.39-7.37 (m, 2H), 7.17 (d, *J* = 8.4 Hz, 2H). ^{31}P NMR (162 MHz, $CDCl_3$): δ 41.4 (s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ 124.8 (d, *J* = 5.1 Hz), 128.7 (d, *J* = 13.1 Hz), 129.3 (d, *J* = 1.4 Hz), 131.6 (d, *J* = 10.2 Hz), 132.3 (d, *J* = 106.5 Hz), 132.5 (d, *J* = 2.9 Hz), 135.5 (d, *J* = 2.2 Hz), 136.5 (d, *J* = 3.6 Hz).

4.2.9. **S-(4-bromophenyl) diphenylphosphinothioate (3i):** White solid (220 mg, 57 %). M.p.: 102-103 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 7.87-7.82 (m, 4H), 7.51-7.48 (m, 2H), 7.45-7.40 (m, 4H), 7.33-7.29 (m, 4H). ^{31}P NMR (162 MHz, $CDCl_3$): δ 41.3 (s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ 123.8 (d, *J* = 2.9 Hz), 125.5 (d, *J* = 5.1 Hz), 128.7 (d, *J* = 13.1 Hz), 131.6 (d, *J* = 10.2 Hz), 132.2 (d, *J* = 106.4 Hz), 132.3 (d, *J* = 2.2 Hz), 132.6 (d, *J* = 2.9 Hz), 136.8 (d, *J* = 3.7 Hz).

4.2.10. **S-(2-methylphenyl) diphenylphosphinothioate (3j):** White solid (263 mg, 81 %). M.p.: 69-71 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 7.87-7.83 (m, 4H), 7.51-7.48 (m, 2H), 7.45-7.41 (m, 4H), 7.24-7.22 (m, 2H). 7.08-7.03 (m, 2H), 2.21(s, 3H). ^{31}P NMR (162 MHz, $CDCl_3$): δ 41.2 (s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ 21.2, 125.7 (d, *J* = 3.7 Hz), 128.5 (d, *J* = 10.1 Hz), 128.9, 129.8 (d, *J* = 1.9 Hz), 131.7 (d, *J* = 7.4 Hz), 132.3 (d, *J* = 2.8 Hz), 132.4 (d, *J* = 3.6 Hz), 132.7 (d, *J* = 84.6 Hz), 136.1 (d, *J* = 2.8 Hz), 139.0 (d, *J* = 1.8 Hz).

4.2.11. **S-(3-methylphenyl) diphenylphosphinothioate (3k):** White solid (263 mg, 81 %). M.p.: 103-105 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 7.87-7.83 (m, 4H), 7.52-7.49 (m, 2H), 7.46-7.42 (m, 4H), 7.24-7.22 (m, 2H). 7.09-7.04 (m, 2H), 2.21 (s, 3H). ^{31}P NMR (162 MHz, $CDCl_3$): δ 42.0 (s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ 21.2, 125.7 (d, *J* = 4.6 Hz), 128.5 (d, *J* = 11.1 Hz), 128.9, 129.8 (d, *J* = 1.9 Hz), 131.7 (d, *J* = 8.2 Hz), 132.3 (d, *J* = 1.8 Hz), 132.4 (d, *J* = 2.7 Hz), 132.7 (d, *J* = 85.5 Hz), 136.1 (d, *J* = 3.7 Hz), 139.0.

4.2.12. **S-(2-methoxyphenyl) diphenylphosphinothioate (3l):** Colorless oil (283 mg, 83 %). ^1H NMR (400 MHz, $CDCl_3$): δ 7.89-7.85 (m, 4H), 7.70 (d, *J*=6.0 Hz, 1H), 7.47-7.44 (m, 2H), 7.40-7.37 (m, 4H), 7.20 (t, *J*=6.4 Hz, 1H), 6.84 (t, *J*=6.0 Hz, 1H), 6.68 (t, *J*=6.4 Hz, 1H), 3.60 (s, 3H). ^{31}P NMR (162 MHz, $CDCl_3$): δ 41.4 (s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ 55.5, 111.1, 114.1 (d, *J* = 3.7 Hz), 121.2 (d, *J* = 1.8 Hz), 128.3 (d, *J* = 10.1 Hz), 130.7, 131.6 (d, *J* = 8.3 Hz), 132.2 (d, *J* = 2.8 Hz), 133.1 (d, *J* = 84.5 Hz), 137.6(d, *J* = 3.7 Hz), 159.4 (d, *J* = 2.8 Hz).

4.2.13. **S-(3-methoxyphenyl) diphenylphosphinothioate (3m):** White solid (243 mg, 77 %). M.p.: 89-90 °C. ^1H NMR (400 MHz, $CDCl_3$): δ 7.88-7.84 (m, 4H), 7.53 -7.50 (m, 2H), 7.46-7.43 (m, 4H), 7.10 (t, *J*=6.0 Hz, 1H), 7.05-7.03(m, 1H), 6.98-6.97 (m, 1H), 6.80-6.78 (m, 1H). 3.66 (s, 3H) ^{31}P NMR (162 MHz, $CDCl_3$): δ 41.3 (s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ 55.3, 115.6, 119.7 (d, *J* = 2.7 Hz), 127.1 (d, *J* = 3.6 Hz), 127.6 (d, *J* = 3.7 Hz), 128.6 (d, *J* = 11.0 Hz), 129.8 (d, *J* = 1.9 Hz), 131.7(d, *J* = 8.2Hz), 132.3(d, *J* = 1. 9Hz), 132.6 (d, *J* = 85.5Hz), 159.6.

4.2.14. **S-(2-ethylphenyl) diphenylphosphinothioate (3n):** White solid (201 mg, 62 %). M.p.: 66-68 °C. IR (KBr):1435, 1198, 1106, 750, 694, 562, 552cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 7.84-7.80 (m, 4 H), 7.51-7.48 (m, 3H), 7.44-7.41 (m, 4H), 7.22-7.19 (m, 1H), 7.15-7.14 (m, 1H), 7.02-7.00 (m, 1H), 2.75 (q, *J*=6.0Hz, 2H), 1.12 (t, *J*=6.0Hz, 3H). ^{31}P NMR (162 MHz, $CDCl_3$): δ 40.7(s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.9, 27.4, 125.0(d, *J* = 3.7 Hz), 126.4 (d, *J* = 1.9 Hz), 128.5 (d, *J* = 10.1 Hz), 129.1, 129.5, 131.5 (d, *J* = 8.3Hz), 132.3 (d, *J* = 1.8Hz), 132.8 (d, *J* = 85.4 Hz), 136.8 (d, *J* = 2.8 Hz), 148.4 (d, *J* =3.7 Hz). MS (ESI, m/z): 339.1 $(M+H)^+$. HRMS (ESI): calcd. For $C_{20}H_{19}OPS$ $(M+H)^+$: 339.09, found: 339.0958.

4.2.15. **S-(2,6-dimethylphenyl) diphenylphosphinothioate (3o):** White solid (237 mg, 70 %). M.p.: 98-99 °C. IR (KBr):1461, 1436, 1202, 1108, 785, 750, 692, 555, 524cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ 7.77-7.73 (m, 4 H), 7.54-7.52 (m, 2H), 7.44-7.40 (m, 4H), 7.12-7.09 (m, 1H), 7.02-7.00 (m, 2H), 2.29 (s, 6H). ^{31}P NMR (162 MHz, $CDCl_3$): δ 39.7(s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ 22.6, 124.5(d, *J* = 4.6 Hz), 128.40 (d, *J* = 1.8 Hz), 128.42 (d, *J* = 11.0 Hz), 129.3 (d, *J* = 1.9 Hz), 131.4 (d, *J* = 8.2Hz), 132.3 (d, *J* = 1.9 Hz), 133.2 (d, *J* = 84.6 Hz), 145.2 (d, *J* =2.6 Hz). MS (ESI, m/z): 339.1 $(M+H)^+$. HRMS (ESI): calcd. For $C_{20}H_{19}OPS$ $(M+H)^+$: 339.09, found: 339.0959.

4.2.16. **S-*p*-tolyl di-*p*-tolylphosphinothioate (3p):** White solid (203 mg, 58 %). M.p.: 79-82 °C. ^1H NMR (400 MHz, $CDCl_3$): δ

7.74-7.70 (m, 4 H), 7.34-7.32 (m, 2H), 7.23-7.21 (m, 4H), 7.00-6.98 (m, 2H), 2.35 (s, 6H), 2.23 (s, 3H). ^{31}P NMR (162 MHz, $CDCl_3$): δ 41.5(s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ 21.1, 21.6, 122.9(d, *J* = 3.7 Hz), 129.2 (d, *J* = 11.0 Hz), 129.8 (d, *J* = 86.4Hz), 129.9, 131.7 (d, *J* = 8.3Hz), 135.2 (d, *J* = 2.8 Hz), 138.9 (d, *J* = 1.9 Hz), 142.7 (d, *J* =2.8 Hz).

4.2.17. **S-*p*-tolyl bis(4-chlorophenyl)phosphinothioate (3q):** White solid (231 mg, 57 %). M.p.: 107-109 °C. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.78-7.74 (m, 4 H), 7.43-7.40 (m, 4H), 7.32-7.30 (m, 2H), 7.04-7.02 (m, 2H), 2.26 (s, 3H). ^{31}P NMR (162 MHz, $CDCl_3$): δ 38.9(s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ 21.2, 121.6 (d, *J* = 3.7 Hz), 129.0 (d, *J* = 11.1 Hz), 130.2, 131.0 (d, *J* = 86.4Hz), 133.0 (d, *J* = 9.2 Hz), 135.3(d, *J* = 2.8 Hz), 139.1 (d, *J* =2.7 Hz), 139.6 (d, *J* =1.8 Hz).

4.2.18 .**6((4(tertbutyl)phenyl)thio)6Hdibenzo[c,e][1,2]oxaphosphinine 6-oxide(3r):** Colorless oil (168 mg, 45 %). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.96-7.92 (m, 1 H), 7.79-7.76 (m, 1H), 7.66-7.64 (m, 2H), 7.50-7.46 (m, 1H), 7.32-7.29 (m, 1H), 7.15-7.01 (m, 6H), 1.19 (s, 9H). ^{31}P NMR (162 MHz, $CDCl_3$): δ 34.6(s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ 31.1, 34.6, 120.0 (d, *J* = 5.5 Hz), 120.3 (d, *J* = 4.6 Hz), 121.7 (d, *J*= 9.2 Hz), 123.0 (d, *J* = 9.2 Hz), 124.5, 124.7, 124.8 (d, *J* = 106.6 Hz), 126.1(d, *J* = 1.8 Hz), 128.5 (d, *J* =11.9 Hz), 130.4, 130.8 (d, *J* =7.3 Hz), 133.7 (d, *J* =1.9 Hz), 135.9 (d, *J* =2.8 Hz), 136.5 (d, *J* =5.5 Hz), 150.8 (d, *J* =8.3 Hz), 152.7 (d, *J* =2.7 Hz).

4.2.19. **O-ethyl S-phenyl phenylphosphonothioate (3s):** Yellow oil (175 mg, 63 %). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.66 (m, 2H), 7.50 (t, *J* = 7.2 Hz, 1H), 7.40-7.35 (m, 2H), 7.32-7.27 (m, 3H), 7.21 (t, *J* = 7.6 Hz, 2H), 4.41-4.31 (m, 2H), 1.41 (t, *J* = 6.8 Hz, 3H). ^{31}P NMR (162 MHz, $CDCl_3$): δ41.7 (s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ 16.3 (d, *J* = 6.5 Hz), 62.5 (d, *J* = 6.5 Hz), 126.6 (d, *J* = 5.1 Hz), 128.2 (d, *J* = 14.6 Hz), 129.0 (d, *J* = 2.9 Hz), 129.1 (d, *J* = 2.2 Hz), 131.47 (d, *J* = 10.2 Hz), 131.54 (d, *J* = 150.2 Hz), 132.5 (d, *J* = 3.0 Hz), 135.5 (d, *J* = 4.3 Hz).

4.2.20 **O-butyl S-phenyl phenylphosphonothioate (3t):** Yellow oil (221 mg, 72 %). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.67-7.62 (m, 2H), 7.51-7.49 (m, 1H), 7.39-7.34 (m, 2H), 7.31-7.26 (m, 3H), 7.20 (t, *J* = 7.2 Hz, 2H), 4.35-4.22 (m, 2H), 1.77-1.70 (m, 2H), 1.48-1.39 (m, 2H), 0.94 (t, *J* = 7.6 Hz, 3H). ^{31}P NMR (162 MHz, $CDCl_3$): δ41.5 (s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ 13.6, 18.8, 32.4 (d, *J* = 6.5 Hz), 66.1 (d, *J* = 7.3 Hz), 126.7 (d, *J* = 5.1 Hz), 128.2 (d, *J* = 15.3 Hz), 128.9 (d, *J* = 2.9 Hz), 129.1 (d, *J* = 2.2 Hz), 131.4 (d, *J* = 10.2 Hz), 131.6 (d, *J* = 149.5 Hz), 132.5 (d, *J* = 2.9 Hz), 135.5 (d, *J* = 4.4 Hz).

4.3 Procedure for the Preparation of 3u-3v.

P(O)H compounds 1 (1.2 mmol), thiols 2 (1.0 mmol), and Na_2CO_3 (1.2 mmol) were placed in a Schlenk tube. Then DMF (10 mL) was added. The reaction mixture was stirred at room temperature for 6 h. After the reaction was completed (monitored by TLC), H_2O (20.0 mL) was added, and the mixture was extracted by CH_2Cl_2 (3*10.0 mL). The combined organic layer was dried over anhydrous Na_2SO_4, filtered, and concentrated by rotary evaporation. The crude reaction mixture was purified by flash column chromatography on silica gel to afford the corresponding product.

4.3.1. **O,O-diethyl S-phenyl phosphorothioate (3u):** Light yellow oil (127 mg, 52 %). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.59-7.56 (m, 2H), 7.37-7.35 (m, 3H), 4.27-4.11 (m, 4H), 1.33-1.29 (m, 6H). ^{31}P NMR (162 MHz, $CDCl_3$): δ22.8 (s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ 16.0 (d, *J* = 7.3 Hz), 64.1 (d, *J* = 5.8 Hz), 126.6 (d, *J* = 7.3 Hz), 129.0 (d, *J* = 2.9 Hz), 129.4 (d, *J* = 2.2 Hz), 134.6 (d, *J* = 5.1 Hz).

4.3.2 **O,O-diethyl S-p-tolylphosphorothioate (3v):** Light yellow oil (187 mg, 72 %). ^{1}H NMR (400 MHz,$CDCl_3$): δ7.44 (dd, J_1 = 8.0 Hz, J_2 = 1.6 Hz, 2H), 7.16 (d, *J* = 8.0 Hz, 2H), 4.26-4.11 (m, 4H), 2.34 (s, 3H), 1.33-1.29 (td, J_1 = 6.8 Hz, J_2 = 0.8 Hz, 6H). ^{31}P NMR (162 MHz, $CDCl_3$): δ23.8 (s, 1P). ^{13}C NMR (100 MHz, $CDCl_3$): δ 16.0 (d, *J* = 7.3 Hz), 21.2, 64.0 (d, *J* = 6.6 Hz), 122.8 (d, *J* = 7.3 Hz), 130.2 (d, *J* = 2.2 Hz), 134.6 (d, *J* = 5.1 Hz), 139.3 (d, *J* = 2.9 Hz).

Acknowledgments

This work was founded by Research Foundation of Qingdao Fusilin Chemical Science &Technology Co., Ltd. (FSL-RF 2016), National Natural Science Foundation of China (Grant No. 21676285 and 21306214) and Qingdao Indigenous Innovation Program (No. 15-9-1-76-jch).

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18. While the manuscript was under preparation, a related process was published; see: Song, S; Zhang, Y-Q; Yeerlan, A; Zhu, B-C, Liu,, J-Z; Jiao, N. *Angew. Chem. Int. Ed.* **2017**, *56*, 1-6.
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