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Phosphonylated Thiocarbonyl Ylides from the Reaction of Aromatic Thioketones with Diethyl Diazomethylphosphonates

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Abstract

The reaction of diazomethylphosphonates with aromatic thioketones at $-65\text{ }^{\circ}\text{C}$ to room temperature yields 2,5-dihydro-1,3,4-thiadiazole-2-phosphonates, which eliminate N_2 to give phosphonylated thiocarbonyl ylides as reactive intermediates. These sulfur-centered 1,3-dipoles undergo typical reactions of thiocarbonyl ylides, *i.e.*, 1,3-dipolar cycloadditions,

Keywords: Diazo compounds; Thioketones; Thiocarbonyl ylides; [2+3] Cycloadditions;

Cyclodimerization; X-Ray crystallography

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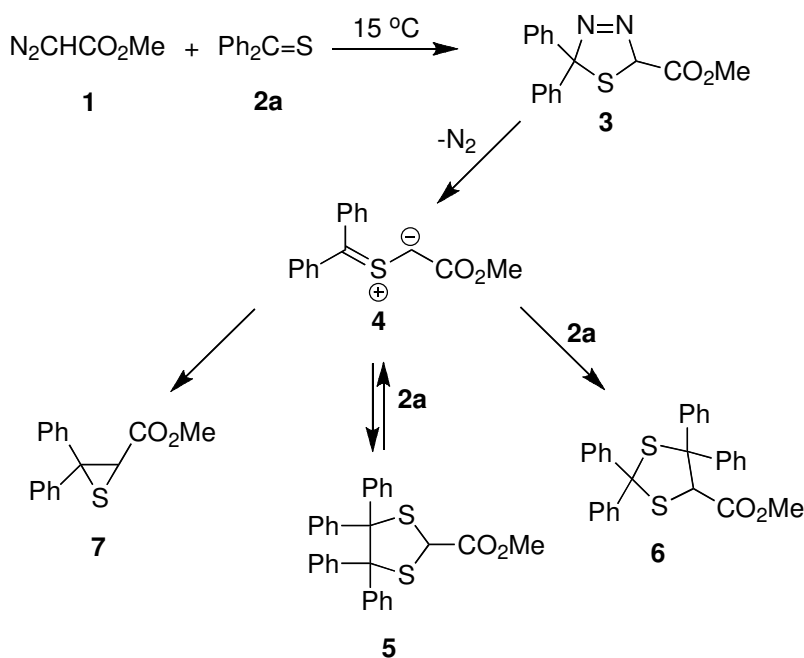
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cyclodimerisation, and electrocyclic ring closure, depending on the involved thioketone and, therefore, on the reaction conditions. In the case of the most reactive thiofluorenone, the phosphonylated thiocarbonyl methanide can be intercepted with thiobenzophenone, a phosphonodithioformate, and tetracyanoethylene. In the absence of such reactive dipolarophiles, cyclodimerization occurs to give the corresponding 1,4-dithiane.

1. Introduction

In contrast to the widely explored diazoacetates,² diazomethylphosphonates are rarely used in 1,3-dipolar cycloadditions. Only recently have reactions with imines to give 4,5-dihydro-1,2,3-thiazole-4-phosphonates or aziridine-2-phosphonates been reported.³ It is well established that reactions of diazocompounds with thiocarbonyl dipolarophiles lead to 2,5-dihydro-1,3,4-thiadiazoles, which offer a convenient access to reactive thiocarbonyl ylides.^{4,5}



Scheme 1.

Diazoacetates were also applied in this reaction, even at a time when the reaction mechanism of the formation of thiiranes and 1,3-dithiolanes was not known.^{6,7} The reaction of methyl

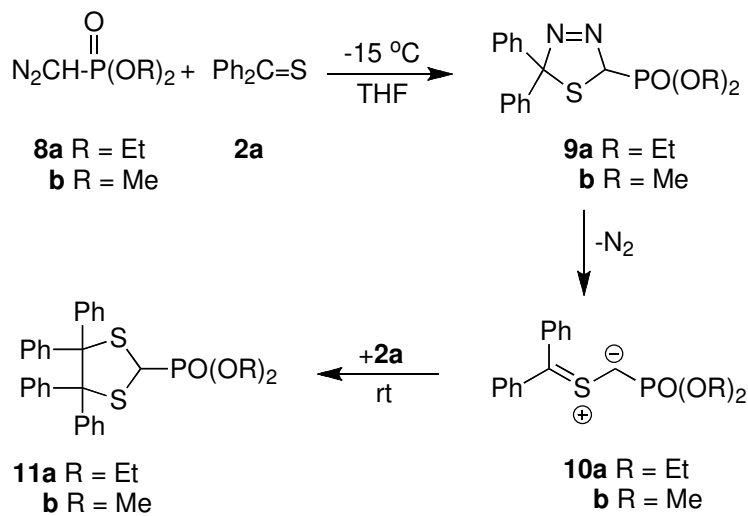
diazoacetate (**1**) with thiobenzophenone (**2a**) was a key experiment in the elucidation of the reaction mechanism of the formation of 1,3-dithiolanes (so-called Schönberg products).⁸ Interestingly, the regioisomeric 1,3-dithiolanes **5** and **6** were formed in a ratio of 1:1. The analogous reaction with 9*H*-fluorene-9-thione (**2b**) was reported to give the corresponding product of type **5** exclusively. Heating of the 'labile' isomer **5** to 100 °C resulted in the formation of a mixture of **6** and methyl 3,3-diphenylacrylate, which is the product of desulfurization of thiirane **7** (Scheme 1). The later reported reaction of diazoacetate with 9*H*-xanthene-9-thione (**2c**), which is less reactive than **2a**, in THF at 60 °C yielded only the corresponding acrylate.⁹ In the same paper, the reaction of ethyl diazoacetate with sterically hindered cycloaliphatic thiones, derived from 2,2,4,4-tetramethylcyclobutane-1,3-dione, were reported to give only thiiranes. In a reaction of adamantanethione with ethyl diazoacetate, which was catalysed by LiClO₄, the sterically less hindered 1,3-dithiolane of type **6** was the sole product.⁹ More complex reaction mixtures were obtained when ethyl diazoacetate was reacted with 4,4-disubstituted 1,3-thiazole-5(4*H*)-thiones.¹⁰

Phosphonylated thiocarbonyl ylides are attractive building blocks for the synthesis of phosphonylated sulfur heterocycles, which are difficult to access by other methods. Recently, these versatile dipolar species were generated from diazomethane and dialkyl phosphonodithioformates.^{11,12} In the present paper, a different approach based on [2+3] cycloaddition of diazomethylphosphonates (**8**) with aromatic thioketones is described.

2. Results and discussion

Unlike the reaction with methyl diazoacetate (**1**, Scheme 1), the blue solution of thiobenzophenone (**2a**) in THF decolorized within *ca.* 30 min of the addition of an equimolar amount of **8a** at -15 °C, which indicates that **8a** is significantly more reactive than **1**. During the reaction, a slow evolution of nitrogen was observed. At room temperature, addition of **8a** to a solution of **2a** or *vice versa* was accompanied by a vigorous gas evolution. In the crude reaction mixture, a new product **11a** and unconsumed **8a** were found in a ratio of *ca.* 1:1 (¹H NMR). By trituration with hexane, **11a** was isolated as a colorless solid. Its structure was established as the symmetrical 1,3-dithiolane on the basis of its ¹H and ¹³C NMR spectra (Scheme 2). The most indicative signal is that for C(4) and C(5) appearing at 79.6 ppm (³J_{C,P} = 7 Hz). The signal of

C(2), which bears the phosphonate group, is located at 40.8 ppm as a doublet with $^1J_{C,P} = 150.9$ Hz. An analogous result was obtained in the case of dimethyl diazomethylphosphonate (**8b**).



Scheme 2.

Finally, the structure of **11a** was established by X-ray crystallography (Figure 1). The five-membered heterocycle has a half-chair conformation twisted on S(1)–C(5). One ethyl group is disordered over two conformations.

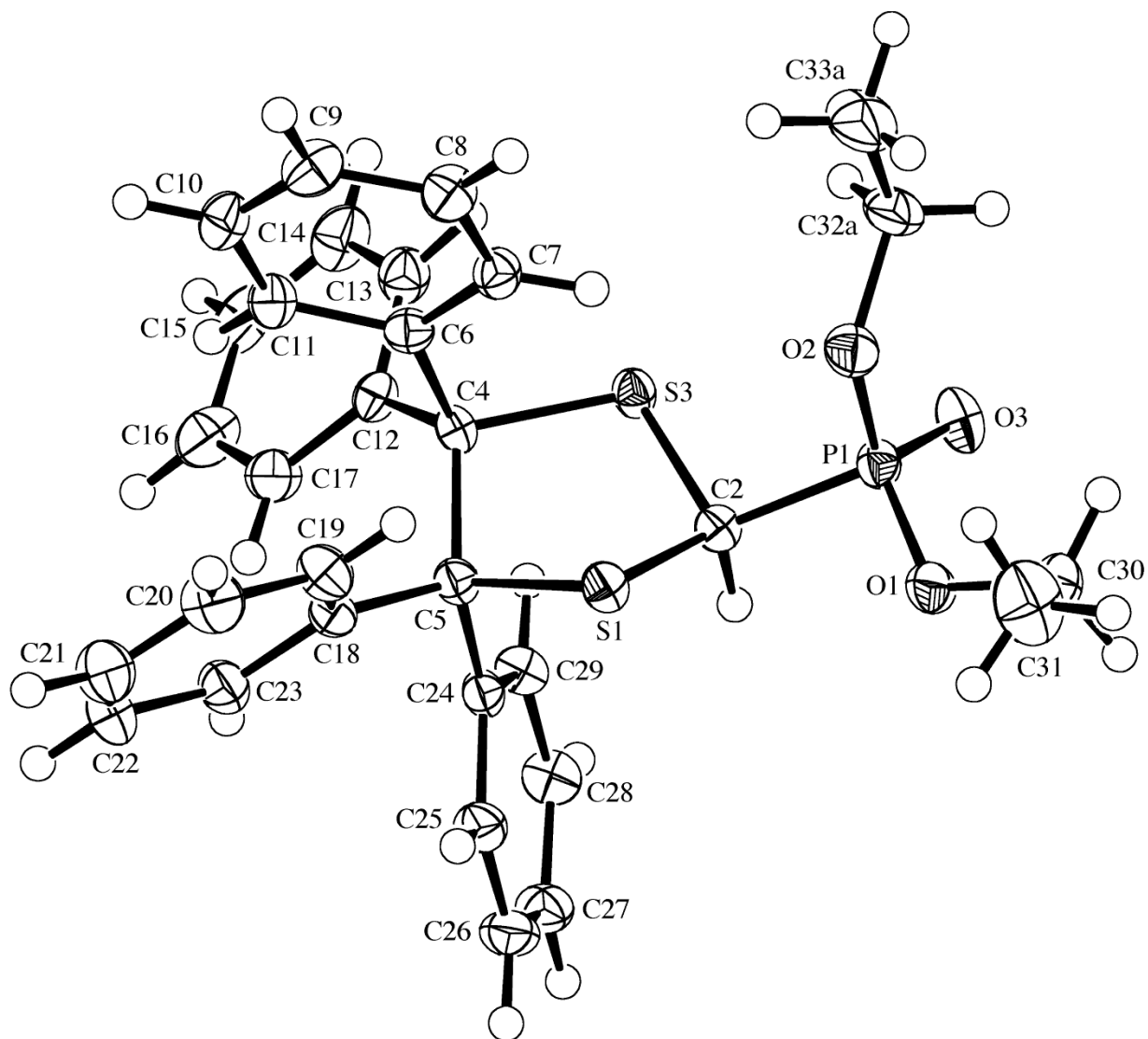
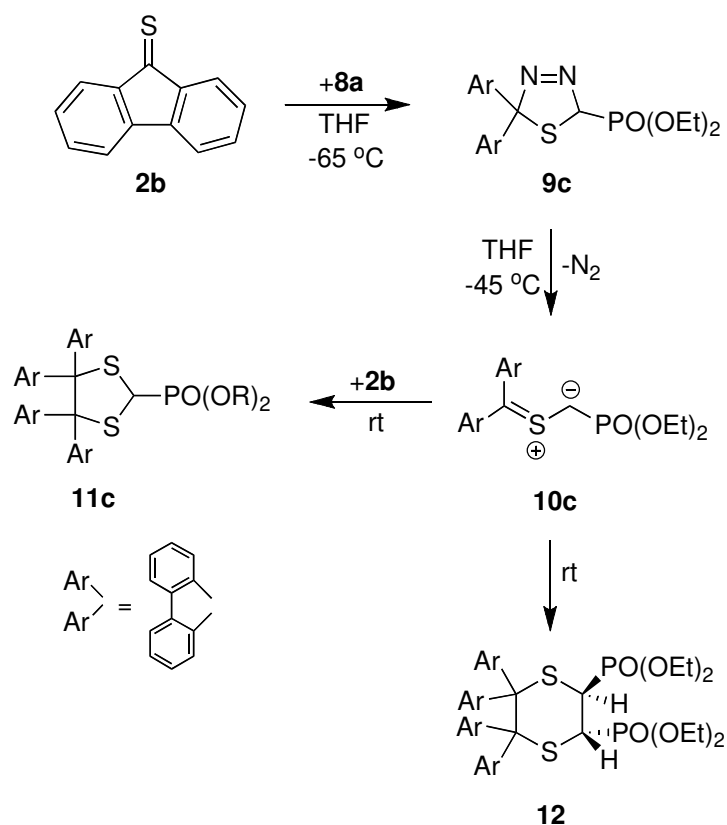


Figure 1. ORTEP-Plot¹⁴ of the molecular structure (conformation A) of **11a** (arbitrary numbering of atoms, 50% probability ellipsoids)

In comparison with the result obtained with **1** (Scheme 1), the most important difference is that only the sterically more congested 1,3-dithiolane was formed, *i.e.* the [2+3] cycloaddition of **10** with **2a** occurs with high regioselectivity.

According to the reactivity scale elaborated for the [2+3] cycloaddition of diphenyldiazomethane and C=S dipolarophiles, 9*H*-fluoren-9-thione (**2b**) is approximately 100× more reactive than **2a**.¹³

The enhanced reactivity of **2b** was confirmed in the reaction with **8a**. The decolorization of the 1:1 mixture occurred smoothly at $-65\text{ }^{\circ}\text{C}$ without evolution of nitrogen. The evolution of N_2 started between -50 and $-45\text{ }^{\circ}\text{C}$, and after warming to room temperature, the crude mixture showed the presence of a single product ($^1\text{H NMR}$), with a characteristic signal at 4.84 ppm ($^2J_{\text{H,P}} = 24.9\text{ Hz}$, $^3J_{\text{H,P}} = 12.6\text{ Hz}$). The integration of this signal, which originates from **8a**, and the aromatic protons reveals a ratio of 1:8, which indicates that the starting materials reacted in a 1:1 ratio. The elemental analysis was in accordance with the values for the thiocarbonyl ylide **10c**, while the CI-MS showed the $[M+1]^+$ peak at m/z 693. Therefore, the isolated product is a dimer of **10c**. Finally, the structure of the compound was established by X-ray crystallography (Figure 2) as the *trans*-1,4-dithiane-2,3-diphosphonate **12** (Scheme 3). The six-membered heterocycle has a chair conformation with the phosphonate substituents in equatorial positions. The fluorene groups are quite planar. The terminal methyl group of one ethoxy group is disordered over two conformations.



Scheme 3.

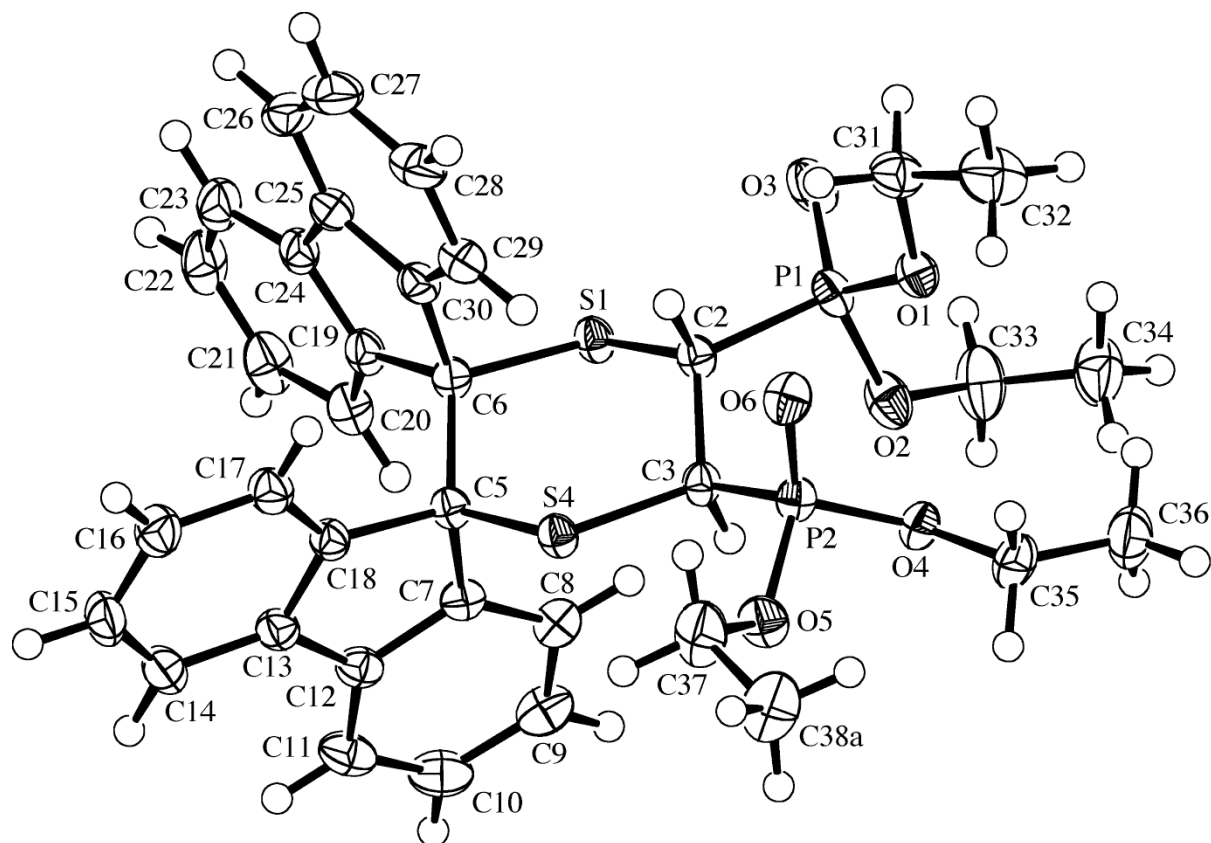
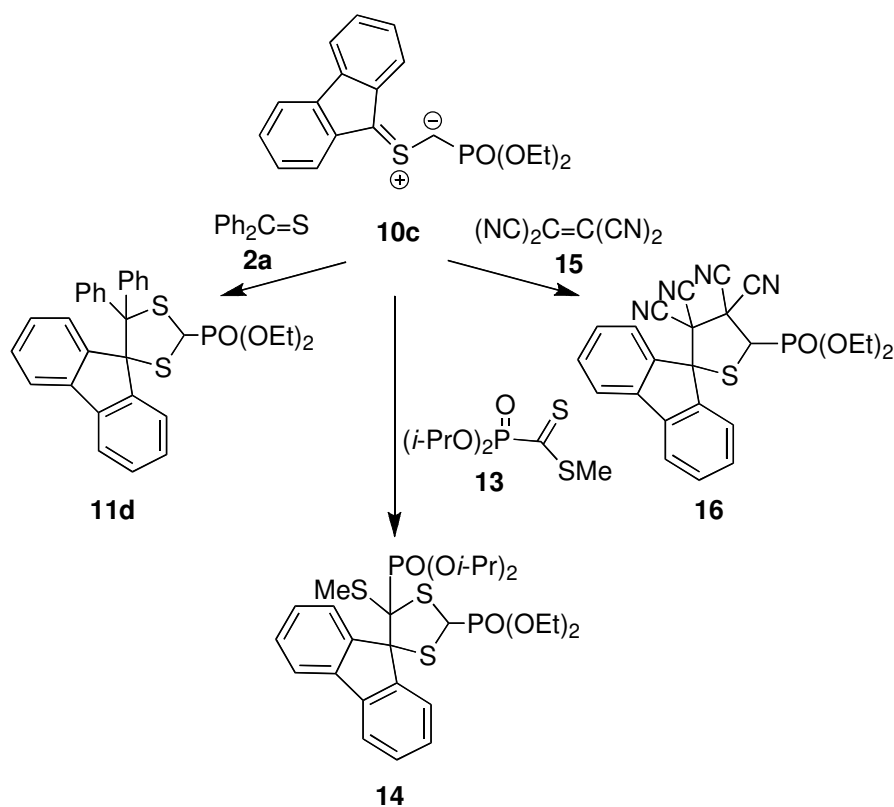


Figure 2. ORTEP-Plot¹⁴ of the molecular structure (conformation A) of **12** (arbitrary numbering of atoms, 50% probability ellipsoids)

The experiment shows that the highly reactive **2b** already undergoes the [2+3] cycloaddition with **8a** at $-65\text{ }^{\circ}\text{C}$ to give regioselectively the 2,5-dihydro-1,3,4-thiadiazole **9c**, which is stable at this temperature. The decomposition starts only at *ca.* $-45\text{ }^{\circ}\text{C}$, and thiocarbonyl ylide **10c** is formed as a transient species. In the absence of any intercepting agent, **10c** dimerizes regio- and stereoselectively to give **12** exclusively. Under these conditions, the 1,3-dipolar electrocyclozation to the corresponding thiirane is completely suppressed by the dimerization process. The mechanism of the head-to-head dimerization can be formulated in line with earlier results to occur via a 1,6-diradical.¹⁵

When **2b** was added to a freshly prepared solution of **9c** at $-65\text{ }^{\circ}\text{C}$ and the mixture was subsequently warmed to room temperature, typical workup by crystallization gave the 1,3-

dithiolane-2-phosphonate **11c** in almost quantitative yield (Scheme 3). Similarly to **11a**, in the ^1H NMR spectrum, H-C(2) absorbs at 5.52 ppm as a doublet ($^2J_{\text{H,P}} = 6.6$ Hz), and C(2) appears as a doublet at 43.6 ppm ($^1J_{\text{C,P}} = 152.4$ Hz). As no dimer **12** could be detected in the crude mixture (^1H NMR), thiocarbonyl ylide **10c** must have been trapped completely by the “superdipolarophile” **2b**. A similar result was obtained with **2a** instead of **2b**. Also in this case, no dimerization was observed, and the structure of the mixed 1,3-dithiolane **11d** was attributed to the product isolated by crystallization (Scheme 4).

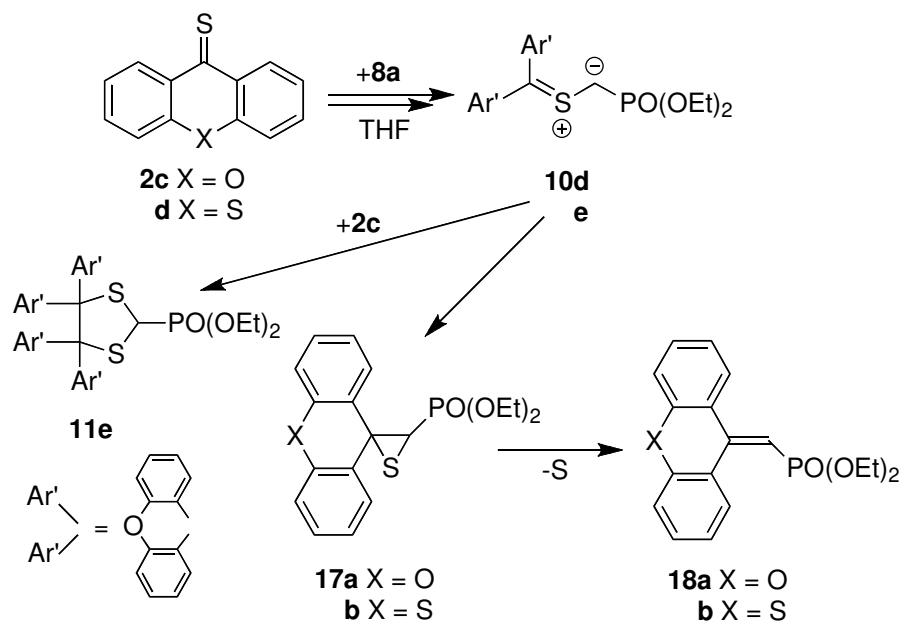


Scheme 4.

In addition to the thioketones **2a** and **2b**, *S*-methyl diisopropyl phosphonodithioformate (**13**) was tested as a C=S dipolarophile. Recently, it has been shown that **13** is an efficient interceptor of aromatic and cycloaliphatic thiocarbonyl *S*-methanides.¹⁶ The reaction with **10c**, generated at -45 °C, led to the expected 1,3-dithiolane-2,4-diphosphonate **14**¹⁷ (Scheme 4). Again, neither the corresponding thiirane nor the dimer could be detected. Therefore it can be concluded that **13** is a superior dipolarophile, comparable with the frequently used **2a** and **2b**.

From the selected C,C-dipolarophiles, *i.e.* maleic anhydride, *N*-cyclohexylmaleimide, and tetracyanoethane, only the latter was able to trap **10c** to yield tetrahydrothiophene **16** (Scheme 4). No formation of any side-product was observed in this reaction.

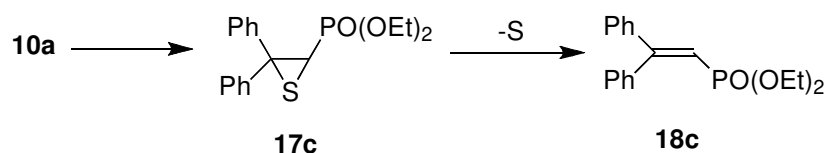
It is well known that 9*H*-xanthene-9-thione (**2c**) and 9*H*-thioxanthene-9-thione (**2d**) belong to the moderately reactive aromatic thioketones.¹³ With **8a** in THF, **2c** reacted slowly at room temperature with evolution of nitrogen. The mixture decolorized within 24 h and gave two products **11e** and **18a** in a ratio of 5:1 (Scheme 5). In the ¹H NMR spectrum, **11e** showed a doublet at 5.53 ppm (¹*J*_{H,P} = 6.1 Hz), whereas the corresponding signal of **18a** appeared at 5.92 ppm (¹*J*_{H,P} = 8.9 Hz). The same products were obtained when the reaction was carried out in boiling THF, but in this case, the ratio was determined as 2:3. Finally, after addition of **2c** to a boiling solution of **8a** in toluene, only the vinyl phosphonate **18a** was formed. In this system, the intermediate **10d** undergoes an electrocyclic ring closure to give **17a** or enter a competitive [2+3] cycloaddition with the parent thioketone **2c**. Spontaneous desulfurization of **17a** leads to the isolated product **18a**. Consequently, higher dilution and increased temperature favor the formation of **18a**.



Scheme 5.

The less reactive **2d** reacted with **8a** only at enhanced temperature to give two products characterised as thiirane **17b** and vinylphosphonate **18b**, but no formation of a 1,3-dithiolane of type **11** was observed. Whereas the doublet for =CH– of **18b** absorbs in the ¹H NMR spectrum in the typical region at *ca.* 6 ppm, the signal of the corresponding H-C(2) of **17b** was found at 2.74 ppm (¹J_{H,P} = 11.0 Hz). In boiling THF, the ratio of the two products was *ca.* 9:1 in favor of **17b**, whereas in boiling toluene, the proportion of **18b** increased (ratio 3:1). The separation of the products was achieved by chromatography.

Prompted by the results obtained with **2c** and **2d**, the reactions of **8a** with **2a** and **2b** (Scheme 2) were repeated in boiling toluene. In the case of **2a**, the corresponding vinylphosphonate **18c** was obtained as the sole product (Scheme 6). However, the reaction with **2b**, despite higher dilution, led to 1,3-dithiolane **11c** (Scheme 3) exclusively, which confirmed the outstanding dipolarophilicity of this thioketone.



Scheme 6.

3. Conclusion

In conclusion, the described results show that diazomethylphosphonates are attractive reagents for 1,3-dipolar cycloadditions, which in the case of C=S dipolarophiles exceed the reactivity of the frequently used diazoacetates. The presence of the phosphono group strongly influences the reactivity of the resulting thiocarbonyl ylides. The synthetic applications of these intermediates are limited by the availability of their precursors, and only ‘thiofluorenone’ **2b** is sufficiently reactive towards **8a** to give the appropriate 2,5-dihydro-1,3,4-thiadiazole derivative **9c**. The dominant tendency for cyclodimerization of **10c** can be suppressed only by addition of very reactive dipolarophiles to the reaction mixture .

4. Experimental

4.1. General

The ^1H and ^{13}C NMR spectra were recorded at *ca.* 21 °C with a Varian Gemini 200 BB VT (^1H at 200.1 MHz, ^{13}C at 50.3 MHz) or a Bruker-AC-300 (^1H at 300.1 MHz, ^{13}C at 75.5 MHz) spectrometer using CDCl_3 as a solvent. Chemical shifts (δ) are reported in ppm downfield from internal TMS. The majority of signals were assigned with the aid of ATP or DEPT spectra. IR spectra were recorded in KBr pellets or as films on a Thermo-Nicolet Nexus FT-IR spectrometer. Low- and high-resolution EI mass spectra (MS and HRMS) were taken on a Finnigan MAT 95 spectrometer at 70 eV. Melting points (uncorrected) were determined in capillary or on a Boëtius apparatus.

Column chromatography was carried out using silica gel (Merck 60, 0.063-0.200 μm). Thin layer chromatography (TLC) was performed on Merck 5554 aluminium-backed SiO_2 plates; products were visualised by UV light.

Toluene and THF were distilled from the blue solution of sodium benzophenone ketyl.

Thiobenzophenone (**2a**),¹⁸ 9*H*-fluorene-9-thione (**2b**),¹⁹ 9*H*-xanthene-9-thione (**2c**)¹⁸ and 9*H*-thioxanthene-9-thione (**2d**)¹⁸ were prepared following the literature procedure.

Methyl and ethyl diazomethylphosphonates (**8**) were prepared by the Seyferth method.²⁰

4.2. Reaction of thiobenzophenone (2a) with diethyl and dimethyl diazomethylphosphonate (8a) and (8b).

To a solution of 1 mmol of thiobenzophenone (**2a**) in dry THF (1 mL) at -65 °C, 1 mmol of diazomethylphosphonate **8a** or **8b**, respectively, was added drop-wise. The mixture was stirred and allowed to warm to room temperature (decolourisation of the mixture was observed at -15 °C). The solvent was evaporated and the solid residue was purified by recrystallization.

An analogous experiment was carried out at room temperature leading to the same result.

4.2.1. Diethyl (4,4,5,5-tetraphenyl-[1,3]dithiolan-2-yl)phosphonate (11a)

Yield: 200 mg (74 %). Colourless solid. Mp 114-118 °C (decomp.; hexane/AcOEt). ^1H NMR: δ 1.41 (t, $J = 7.0$ Hz, 2 CH_3), 4.16 (d, $^2J_{\text{HP}} = 6.6$ Hz, CH), 4.20-4.34 (m, 2 CH_2O), 6.94-7.79 (m, 20 arom. H). ^{13}C NMR: δ 16.4 (d, $^3J_{\text{CP}} = 5.9$ Hz, 2 CH_3), 40.8 (d, $^1J_{\text{CP}} = 150.9$, CHP), 63.6 (d, $^2J_{\text{CP}} = 6.7$ Hz, 2 CH_2O), 79.6 (d, $^3J_{\text{CP}} = 7.0$ Hz, 2 C_q), 126.1, 126.5, 126.6, 127.7, 127.9, 129.0, 131.1, 131.9 (20 arom. CH), 142.4, 142.6 (4 arom. C_q). IR (KBr, cm^{-1}): 3059m, 2981m, 1490s, 1443s, 1258s (P=O), 1043s and 1020s (P-O-C), 738m, 696s, 532m. ESI-MS m/z (%): 569 (100, $[\text{M}+\text{Na}]^+$). Anal. calcd for $\text{C}_{31}\text{H}_{31}\text{O}_3\text{PS}_2$ (546.69): C 68.11, H 5.72; found: C 68.24, H 5.46.

4.2.2. Dimethyl (4,4,5,5-tetraphenyl-[1,3]dithiolan-2-yl)-phosphonate (11b)

Yield: 250 mg (96%). Colourless solid. Mp 84-86 °C (decomp.; hexane/ Et_2O). ^1H NMR: δ 3.90 (d, $^3J_{\text{HP}} = 11$ Hz, 2 CH_3O), 4.20 (d, $^2J_{\text{HP}} = 6.9$ Hz, CH), 6.80-7.70 (m, 20 arom. H). ^{13}C NMR: δ 40.6 (d, $^1J_{\text{CP}} = 151.4$, CHP), 54.3 (d, $^2J_{\text{CP}} = 6.7$ Hz, 2 CH_3O), 79.9 (d, $^3J_{\text{CP}} = 7.3$ Hz, 2 C_q), 126.7, 127.1, 127.3, 131.6, 132.3 (20 arom. CH), 142.9 (4 arom. C_q). IR (KBr, cm^{-1}): 3056m, 2953m, 1490s, 1443s, 1262s (P=O), 1054s and 1032s (P-O-C), 739m, 700s, 532m. EI-MS m/z (%): 518 (< 1 , M^+), 288 (9), 211 (22), 210 (100), 198 (30), 197 (9), 178 (27), 165 (46), 121 (26).

4.3. Reaction of diethyl diazomethylphosphonate (8a) with 9H-fluorene-9-thione (2b)

To a solution of 1 mmol of 9H-fluorene-9-thione (**2b**) in dry THF (1 mL), 1 mmol of diethyl diazomethylphosphonate (**8a**) was added drop-wise at -65 °C. After 10 min stirring at -65 °C, decolourisation of the mixture was observed. For the synthesis of **12**, the mixture was stirred and allowed to warm to room temperature. For the synthesis of **11c-d**, **14**, and **16**, a respective dipolarophile **2a**, **2b**, **13** or **15** (1 mmol) was added. The mixture was stirred and allowed to warm to room temperature. The solvent was removed in vacuum and the solid residue was purified by recrystallization.

4.3.1. Tetraethyl dispiro[9H-fluorene-9,2'-[1,4]dithiane-3',9''-[9H]fluorene]-5',6'-diphosphonate (12)

Yield: 160 mg (46%). Colourless solid. Mp 230-235 °C (decomp.; hexane/dichloromethane). ^1H NMR: δ 1.36 (t, $J = 7.0$ Hz, 2 CH_3), 1.37 (t, $J = 7.0$ Hz, 2 CH_3), 4.16-4.36 (m, 4 CH_2O), 4.84 (dd, $^2J_{\text{HP}} = 24.9$ Hz, $^3J_{\text{HP}} = 12.6$ Hz, 2 CH), 6.16-6.19 (m, 2 arom. H), 6.63-6.69 (m, 2 arom. H), 7.01-7.64 (m, 10 arom. H), 9.05-9.10 (m, 2 arom. H). ^{13}C NMR: δ 16.1 (s, 4 CH_3), 38.0 (d, $^1J_{\text{CP}}$

= 133.1 Hz, 2 CHP), 57.0 (2 C_q), 63.1 (d, ²J_{CP} = 58.6 Hz, 4 CH₂O), 119.1, 120.1, 125.1, 126.4, 126.7, 127.7, 128.4, 128.6 (16 arom. CH), 139.8, 140.5, 142.2, 148.3 (8 arom. C_q). IR (KBr, cm⁻¹): 2983m, 1630w, 1446m, 1249s (P=O), 1023vs (P-O-C), 976s, 742s, 553m. CI-MS (NH₃) *m/z* (%): 693 (100, [M+1]⁺), 329 (21), 318 (45), 197 (17). Anal. calcd for C₃₆H₃₈O₆P₂S₂ (692.77): C 62.42, H 5.53, S 9.26; found: C 62.10, H 5.50, S 9.22.

4.3.2. Diethyl dispiro[9*H*-fluorene-9,4'-[1,3]dithiolan-5',9''-[9*H*]fluorene]-2'-phosphonate (11c)

Yield: 400 mg (74%). Colourless solid. Mp 242-252 °C (decomp.; hexane/dichloromethane). ¹H NMR: δ 1.41 (t, *J* = 7.0 Hz, 2 CH₃), 4.28-4.38 (m, 2 CH₂O), 5.52 (d, ²J_{HP} = 6.6 Hz, CH), 7.09-7.64 (m, 20 arom. H). ¹³C NMR: δ 16.4 (d, ³J_{CP} = 5.8 Hz, 2 CH₃), 43.6 (d, ¹J_{CP} = 152.4, CHP), 63.9 (d, ²J_{CP} = 6.8 Hz, 2 CH₂O), 75.0 (d, ³J_{CP} = 7.0 Hz, 2 C_q), 119.0, 119.5, 126.1, 126.7, 128.6, 128.7 (20 arom. CH), 127.7, 140.1 (4 arom. C_q). IR (KBr, cm⁻¹): 3055m, 2981m, 2905m, 1476m, 1446s, 1259vs (P=O), 1047vs and 1020vs (P-O-C), 964s, 741vs, 650m, 533m. CI-MS (NH₃) *m/z* (%): 562 (15), 561 (37), 560 (100, [M+NH₄]⁺), 543 (15), 349 (13), 348 (17), 329 (21), 202 (28), 200 (15), 197 (27). Anal. calcd for C₃₁H₂₇O₃PS₂ (542.66): C 68.61, H 5.02, S 11.82; found: C 68.50, H 4.95, S 12.33.

4.3.3. Diethyl 5',5'-diphenylspiro[9*H*-fluorene-9,4'-[1,3]dithiolane]-2-phosphonate (11d)

Yield: 200 mg (37%). Colourless solid. Mp 172-178 °C (decomp.; hexane/Et₂O). ¹H NMR: δ 1.42 (t, *J* = 7.0 Hz, 2 CH₃), 4.29-4.38 (m, 2 CH₂O), 5.01 (d, ²J_{HP} = 6.7 Hz, CH), 5.65-5.67 (m, 1 arom. H), 6.73-7.36 (m, 13 arom. H), 7.73-7.80 (m, 4 arom. H). ¹³C NMR: δ 16.5 (d, ³J_{CP} = 6.0 Hz, 2 CH₃), 42.1 (d, ¹J_{CP} = 149.7, CHP), 63.8 (d, ²J_{CP} = 6.9 Hz, CH₂O), 63.9 (d, ²J_{CP} = 6.7 Hz, CH₂O), 75.9, 78.0 (2 C_q), 120.1, 120.5, 124.7, 126.5, 126.7, 127.1, 127.5, 127.7, 128.1, 128.2, 129.0 (18 arom. CH), 132.0, 138.3, 140.4, 142.8, 145.1, 148.0 (6 arom. C_q). IR (KBr, cm⁻¹): 3055m, 2981m, 2905m, 1475m, 1444s, 1257s (P=O), 1046vs and 1020vs (P-O-C), 975s, 745vs, 699s, 536m. CI-MS (NH₃) *m/z* (%): 563 (37, [M+NH₄]⁺), 562 (100), 546 (8, [M+1]⁺), 545 (21, M⁺), 366 (38), 349 (20), 317 (45), 210 (18), 200 (16), 199 (78), 197 (33). Anal. calcd for C₃₁H₂₉O₃PS₂ (544.68): C 68.36, H 5.37, S 11.77; found: C 67.88, H 5.30, S 12.22.

4.3.4. Diisopropyl [2-(diethoxyphosphoryl)-5-methylsulfanylspiro[9*H*-fluorene-9,4'-[1,3]dithiolane]-5-phosphonate (14)

Yield: 260 mg (43%). Colourless solid. Mp 160-170 °C (decomp.; hexane/dichloromethane). ¹H

NMR: δ 0.74 (d, $J = 6.2$ Hz, CH₃), 0.93 (d, $J = 6.2$ Hz, CH₃), 1.16 (d, $J = 6.1$ Hz, CH₃), 1.30 (d, $J = 6.1$ Hz, CH₃), 1.59 (t, $J = 6.9$ Hz, CH₃), 1.60 (t, $J = 6.9$ Hz, CH₃), 2.73 (s, CH₃S), 4.43-4.68 (m, 2 CH₂O, 2 CHO), 5.40 (dd, $^2J_{HP} = 4.6$ Hz, $^4J_{HP} = 1.1$ Hz, CH), 7.36-7.79 (m, 6 arom. H), 8.34-8.37 (m, 1 arom. H), 8.68-8.71 (m, 1 arom. H). ¹³C NMR: δ 16.3 (d, $^3J_{CP} = 7.2$ Hz, CH₃CH₂O), 16.5 (d, $^3J_{CP} = 14.0$ Hz, CH₃CH₂O), 22.0 (d, $^3J_{CP} = 6.4$ Hz, CH₃S), 23.0, 23.5, 23.6, 23.9 (2 (CH₃)₂CH), 42.7 (dd, $^1J_{CP} = 150.0$, $^3J_{CP} = 11.0$ Hz, CHP), 63.6 (d, $^2J_{CP} = 6.9$ Hz, CH₂O), 64.4 (d, $^2J_{CP} = 6.6$ Hz, CH₂O), 71.0 (d, $^2J_{CP} = 8.3$ Hz, (CH₃)₂CH), 73.3 (d, $^2J_{CP} = 7.9$ Hz, (CH₃)₂CH), (2 C_q not found), 118.4, 119.3, 125.9, 126.6, 128.5, 129.1, 129.2, 130.7 (8 arom. CH), 139.2, 140.3, 142.6, 149.4 (4 arom. C_q). IR (KBr, cm⁻¹): 3058w, 2979m, 2925w, 1448m, 1386m, 1256s, 1244s (P=O), 1046s, 1010vs and 985vs (P-O-C), 743vs, 534m. CI-MS (NH₃) m/z (%): 604 (32, [M+1]⁺), 603 (100, M⁺), 389 (28), 375 (11), 202 (12), 200 (16).

4.3.5. Diethyl (3,3,4,4-tetracyano-spiro[9H-fluorene-9,2'-thiolane)-5-phosphonate (16)

Yield: 240 mg (51%). Pale-yellow solid. MP 159-162 °C (decomp.; Et₂O). ¹H NMR: δ 1.40-1.47 (m, 2 CH₃), 4.31-4.44 (m, 2 CH₂O), 4.70 (d, $^2J_{HP} = 16.3$ Hz, CH), 7.18-7.77 (m, 7 arom. H), 8.15-8.17 (m, 1 arom. H). ¹³C NMR: δ 16.2 (d, $^3J_{CP} = 5.1$ Hz, CH₃), 16.2 (d, $^3J_{CP} = 4.6$ Hz, CH₃), 49.5 (d, $^1J_{CP} = 147.3$ Hz, CHP), 52.1, 60.0 (2 C_q), 65.4, (d, $^2J_{CP} = 6.9$ Hz, CH₂O), 65.8, (d, $^2J_{CP} = 6.9$ Hz, CH₂O), 107.5, 109.2, 109.4, 109.5 (4 CN), 120.7, 120.8, 126.6, 128.2, 128.3, 128.7, 131.5, 131.8 (8 arom. C), 139.8, 141.2, 142.7 (4 arom. C_q). IR (KBr, cm⁻¹): 3064w, 2987m, 2920m, 2255w, 1451m, 1264s (P=O), 1043vs and 1017vs (P-O-C), 752s, 744s, 548m. CI-MS (NH₃) m/z (%): 492 (100, [M+NH₄]⁺), 292 (40), 264 (27). Anal. calcd for C₃₁H₁₉N₄O₃PS₂ (474.48): C 60.75, H 4.04, N 11.85, S 6.76; found: C 60.55, H 4.04, N 11.64, S 6.61.

4.4. Reaction of diethyl diazomethylphosphonate (8a) with 9H-xanthene-9-thione (2c) and 9H-thioxanthene-9-thione (2d)

To a solution of 1 mmol of 9H-xanthene-9-thione (2c) in dry THF (1 mL), 1 mmol of diethyl diazomethylphosphonate (8a) was added drop-wise at room temperature. After 24 h stirring, decolourisation of the mixture was observed. The solvent was removed under vacuum and compound 11e was separated and purified by recrystallization. The same reaction in boiling THF gave products 11e and 18a in a 2:3 ratio, whereas in boiling toluene the formation of only 18a was observed. The reaction with 2d was carried out in boiling toluene. Two products were separated chromatographically on silica gel (hexane/AcOEt).

4.4.1. Diethyl Dispiro[9*H*-xanthene-9,4'-[1,3]dithiolane-5',9''-[9*H*]xanthene]-2'-phosphonate (11e)

Yield: 180 mg (63%). Colourless solid. Mp 156-158 °C (decomp.; hexane/dichloromethane). ¹H NMR: δ 1.48 (t, *J* = 7.0 Hz, 2 CH₃), 4.37-4.47 (m, 2 CH₂O), 5.53 (d, ²*J*_{HP} = 6.1 Hz, CH), 6.67-7.52 (m, 14 arom. H), 8.04-8.07 (m, 2 arom. H). ¹³C NMR: δ 16.5 (d, ³*J*_{CP} = 5.8 Hz, 2 CH₃), 43.9 (d, ¹*J*_{CP} = 153.3 Hz, CHP), 63.9 (d, ²*J*_{CP} = 6.9 Hz, 2 CH₂O), 74.5 (d, ³*J*_{CP} = 7.1 Hz, 2 C_q), 115.5, 116.0, 121.9, 128.7, 128.9, 130.3 (16 arom. CH), 151.3, 151.8 (4 arom. C_q). IR (KBr, cm⁻¹): 2983w, 2915w, 1597m, 1474s, 1443s, 1308m, 1281m, 1246s (P=O), 1044s and 1017vs (P-O-C), 749s, 536m. ESI-MS *m/z* (%): 597 ([*M*+Na]⁺). Anal. calcd for C₃₁H₂₇O₅PS₂ (574.65): C 64.53, H 4.68, S 10.95; found: C 64.79, H 4.74, S 11.16.

4.4.2. Diethyl (9*H*-xanthen-9-ylidene)methylphosphonate (18a)

Yield: 200 mg (61%). Colourless solid. Mp 72-73 °C (hexane). ¹H NMR: δ 1.22 (t, *J* = 7.0 Hz, 2 CH₃), 3.98-4.12 (m, 2 CH₂O), 5.92 (d, ²*J*_{HP} = 8.9 Hz, CH), 7.16-7.28 (m, 4 arom. H), 7.38-7.47 (m, 2 arom. H), 7.71-7.74 (m, 1 arom. H), 8.52-8.55 (m, 1 arom. H). ¹³C NMR: δ 16.2 (d, ³*J*_{CP} = 6.6 Hz, 2 CH₃), 61.8 (d, ²*J*_{CP} = 6.0 Hz, 2 CH₂O), 105.3 (d, ¹*J*_{CP} = 198.2 Hz, CHP), 116.6, 117.2 (2 arom. C), 119.8 (d, ²*J*_{CP} = 7.1 Hz, C_q), 123.2, 124.1, 124.2, 129.6, 130.8, 131.5 (8 arom. CH), 143.8, 143.9, 151.3, 152.0 (4 arom. C_q). IR (KBr, cm⁻¹): 3058w, 3033w, 2985m, 2900w, 1604s, 1564m, 1477m, 1456s, 1391w, 1361w, 1320m, 1284m, 124s and 1236s (P=O), 1047s and 1035s (P-O-C), 966s, 788s, 770s, 547m. CI-MS (NH₃) *m/z* (%): 348 (7, [*M*+NH₄]⁺), 333 (8), 332(20), 331 (100, [*M*+1]⁺). Anal. calcd for C₁₈H₁₉O₄P (330.32): C 65.45, H 5.80; found: C 65.30, H 5.92.

4.4.3. Spiro[thiirane-2,9'-[9*H*]thioxanthene]-3-phosphonate (17b)

Yield: 190 mg (50%). Eluted with hexane/AcOEt 1/1 and recrystallized from hexane. Pale-yellow solid. Mp 69-72 °C (hexane). ¹H NMR: δ 1.16 (t, *J* = 7.1 Hz, CH₃), 1.18 (t, *J* = 7.1 Hz, CH₃), 2.74 (d, ²*J*_{HP} = 11.0 Hz, CH), 3.76-3.92 (m, 2 CH₂O), 7.19-7.28 (m, 4 arom. H), 7.45-7.49 (m, 2 arom. H), 7.60-7.63 (m, 1 arom. H), 7.68-7.71 (m, 1 arom. H). ¹³C NMR: δ 16.3 (d, ³*J*_{CP} = 4.2 Hz, 2 CH₃), 40.7 (d, ¹*J*_{CP} = 184.1 Hz, CHP), 55.1 (C_q), 62.4 (d, ²*J*_{CP} = 6.5 Hz, CH₂O), 63.0 (d, ²*J*_{CP} = 6.7 Hz, CH₂O), 126.1, 126.2, 126.6, 126.8, 127.5, 127.7, 130.3 (8 arom. CH), 133.0, 136.1, 136.4, 137.0 (4 arom. C_q). IR (KBr, cm⁻¹): 3057w, 2982m, 2929w, 2904w, 1457m, 1441m, 1263s and 1243m (P=O), 1045s and 1027s (P-O-C), 971s, 787m, 742s, 545m. CI-MS (NH₃) *m/z* (%): 380 (5), 379 (10), 378 (44, *M*⁺), 365 (10), 363 (46), 347 (21), 346 (100, [*M*-S]⁺),

332 (20), 331 (13). Anal. calcd for C₁₈H₁₉O₃PS₂ (378.45): C 57.13, H 5.06, S 16.94; found: C 57.16, H 4.99, S 16.83.

4.4.4. Diethyl (9*H*-thioxanthen-9-ylidene)methylphosphonate (**18b**)

Yield: 100 mg (29%). Eluted with AcOEt and recrystallized from hexane. Colourless solid. Mp 74-75 °C (hexane). ¹H NMR: δ 1.11 (t, *J* = 7.1 Hz, CH₃), 1.12 (t, *J* = 7.1 Hz, CH₃), 3.86-3.97 (m, 2 CH₂O), 5.92 (d, ²*J*_{HP} = 12.5 Hz, CH), 7.26-7.36 (m, 4 arom. H), 7.43-7.49 (m, 2 arom. H), 7.63-7.66 (m, 1 arom. H), 8.19-8.22 (m, 1 arom. H). ¹³C NMR: δ 16.0 (d, ³*J*_{CP} = 6.8 Hz, 2 CH₃), 61.8 (d, ²*J*_{CP} = 6.1 Hz, 2 CH₂O), 115.4 (d, ¹*J*_{CP} = 191.6 Hz, CHP), 125.8, 125.9, 126.1, 126.3, 127.1, 128.4, 128.9, 130.2 (8 arom. CH), 131.9 (d, ²*J*_{CP} = 5.6 Hz, C_q), 136.0, 136.3, 151.9, 152.0 (4 arom. C_q). IR (KBr, cm⁻¹): 3053w, 2980w, 2934w, 2903w, 1586m, 1559w, 1464w, 1438m, 1241s (P=O), 1160w, 1049s and 1035s (P-O-C), 960s, 934w, 843m, 778m, 764m, 548m. CI-MS (NH₃) *m/z* (%): 364 (10, [M+NH₄]⁺), 363 (46), 348 (13), 347 (21), 346 (100, M⁺). Anal. calcd for C₁₈H₁₉O₃PS (346.39): C 62.42, H 5.53, S 9.26; found: C 62.35, H 5.38, S 9.32.

4.5. X-Ray crystal-structure determination of **11a** and **12**

All measurements were performed on a Nonius KappaCCD area-diffractometer²¹ using graphite-monochromated MoK_α radiation (λ 0.71073 Å) and an Oxford Cryosystems Cryostream 700 cooler. The data collection and refinement parameters are given below²² and views of the molecules are shown in Figures 1 and 2. Data reduction was performed with HKL Denzo and Scalepack.²³ The intensities were corrected for Lorentz and polarization effects, and absorption corrections based on the multi-scan method²⁴ were applied. Equivalent reflections were merged. The structures were solved by direct methods using SIR92²⁵ in the case of **11a** and SHELXS97²⁶ in the case of **12**, which revealed the positions of all non-H-atoms. In the case of **11a**, one ethyl group is disordered over two conformations. Two sets of overlapping positions were defined for the atoms of the disordered ethyl group and the site occupation factor of the major conformation of the group refined to 0.818(6). In the case of **12**, the terminal methyl group of one ethoxy moiety is disordered over two conformations. Two positions were defined for the atoms of the disordered methyl group and the site occupation factor of the major conformation refined to 0.51(3). For both structures, similarity restraints were applied to the chemically equivalent bond lengths and angles involving all disordered C-atoms, while neighbouring atoms within and between each conformation of the disordered ethyl groups were restrained to have similar atomic displacement parameters. The non-H-atoms were refined anisotropically. All of the H-atoms were

placed in geometrically calculated positions and refined using a riding model where each H-atom was assigned a fixed isotropic displacement parameter with a value equal to $1.2U_{\text{eq}}$ of its parent C-atom ($1.5U_{\text{eq}}$ for the methyl groups). The refinement of the structures was carried out on F^2 using full-matrix least-squares procedures, which minimized the function $\sum w(F_o^2 - F_c^2)^2$. A correction for secondary extinction was applied in the case of **12**. In **11a** and in **12**, three and one reflections, respectively, whose intensities were considered to be extreme outliers, were omitted from the final refinement. Neutral atom scattering factors for non-H-atoms were taken from²⁷, and the scattering factors for H-atoms were taken from ref.²⁸ Anomalous dispersion effects were included in F_c ;²⁹ the values for f' and f'' were those of ref.³⁰ The values of the mass attenuation coefficients are those of ref.³¹ All calculations were performed using the *SHELXL97*³² program.

Crystal data for **11a**: $\text{C}_{31}\text{H}_{31}\text{O}_3\text{PS}_2$, $M = 546.68$, colourless, prism, crystal dimensions $0.15 \times 0.25 \times 0.32$ mm, triclinic, space group P^-1 , $Z = 2$, reflections for cell determination 32546, 2θ range for cell determination $4 - 50^\circ$, $a = 8.4060(3)$ Å, $b = 9.8163(4)$ Å, $c = 17.4649(7)$ Å, $\alpha = 87.447(3)^\circ$, $\beta = 76.876(2)^\circ$, $\gamma = 77.811(2)^\circ$, $V = 1371.84(9)$ Å³, $T = 160$ K, $D_X = 1.323$ g·cm⁻³, $\mu(\text{MoK}\alpha) = 0.284$ mm⁻¹, scan type ω , $2\theta_{\text{max}} = 50^\circ$, transmission factors (min; max) 0.757; 0.966, total reflections measured 17711, symmetry independent reflections 4832, reflections with $I > 2\sigma(I)$ 3935, reflections used in refinement 4829, parameters refined 356; restraints 38, $R(F)$ [$I > 2\sigma(I)$ reflections] = 0.0407, $wR(F^2)$ [all data] = 0.1055 ($w = [\sigma^2(F_o^2) + (0.0471P)^2 + 0.7354P]^{-1}$, where $P = (F_o^2 + 2F_c^2)/3$), goodness of fit 1.064, final $\Delta_{\text{max}}/\sigma$ 0.002, $\Delta\rho$ (max; min) = 0.34; -0.50 e Å⁻³.

Crystal data for **12**: $\text{C}_{36}\text{H}_{38}\text{O}_6\text{P}_2\text{S}_2$, $M = 692.76$, colourless, prism, crystal dimensions $0.10 \times 0.22 \times 0.22$ mm, monoclinic, space group $P2_1/n$, $Z = 4$, reflections for cell determination 63677, 2θ range for cell determination $4 - 60^\circ$, $a = 12.1758(1)$ Å, $b = 13.0645(1)$ Å, $c = 21.1455(2)$ Å, $\beta = 93.5396(7)^\circ$, $V = 3357.21(5)$ Å³, $T = 160$ K, $D_X = 1.370$ g·cm⁻³, $\mu(\text{MoK}\alpha) = 0.300$ mm⁻¹, scan type ϕ and ω , $2\theta_{\text{max}} = 60^\circ$, transmission factors (min; max) 0.868; 0.973, total reflections measured 89162, symmetry independent reflections 9809, reflections with $I > 2\sigma(I)$ 7639, reflections used in refinement 9808, parameters refined 431; restraints 7, $R(F)$ [$I > 2\sigma(I)$ reflections] = 0.0443, $wR(F^2)$ [all data] = 0.1198 ($w = [\sigma^2(F_o^2) + (0.0536P)^2 + 1.7904P]^{-1}$, where P

= $(F_o^2 + 2F_c^2)/3$), goodness of fit 1.062, secondary extinction coefficient 0.0021(6), final Δ_{\max}/σ 0.001, $\Delta\rho$ (max; min) = 0.36; $-0.53 \text{ e } \text{\AA}^{-3}$.

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Graphical Abstract

