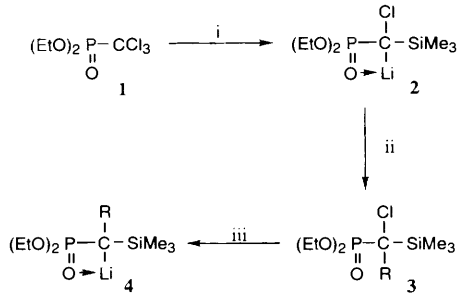
New route to 1-formylalkylphosphonates using diethyl trichloromethylphosphonate as a precursor

Yannick Zanella, Sylvie Berté-Verrando, Rachel Dizière and Philippe Savignac
Hétéroéléments et Coordination, URA CNRS 1499, DCPH, Ecole Polytechnique, 91128 PALAISEAU. Cedex France

Diethyl trichloromethylphosphonate **1** and chlorotrimethylsilane were converted in a three-step sequence by BuLi into α-phosphorylated α-silylated α-substituted carbanions **4**. These, on reaction with ethyl formate in the presence of chlorotrimethylsilane give transient silylated acetals **8** which readily undergo acid hydrolysis to afford 1-formylalkylphosphonates **7** in good yield.

Diethyl trichloromethylphosphonate **1**, which is readily available on laboratory scale[1] and also commercially, has already been cited as a useful starting material.[2] In a preceding paper we described a synthesis of medium size (4–6 membered) cycloalkylphosphonates[3] based on the successive exchange of the three chlorine atoms of the phosphonate **1**. This process, which is summarized in Scheme 1, involves a three-step sequence. In the first step, addition of a mixture of diethyl trichloromethylphosphonate **1** and chlorotrimethylsilane (1.1 equiv.) to an excess of butyllithium (2.1 equiv.) in tetrahydrofuran (THF) at low temperature takes place through a double chlorine–lithium exchange to give the stable α-phosphorylated α-silylated α-chlorinated carbanion **2** [δ_P(THF) +46.9]. With these experimental conditions the condensation of two trimethylsilyl groups was never observed and alkylation of the carbanion **2** was achieved by reaction with alkyl halides[4] (RX with X = Br, I). The so formed phosphonate **3** [δ_P(THF) +24.7] is then submitted to the third chlorine–lithium exchange at low temperature to give a new α-phosphorylated α-silylated α-substituted stable carbanion **4**. One component only was observed by ^{31}P NMR analysis [δ_P(THF) +54] and the signal was assigned to the carbanion **4**. By the use of this sequence a large variety of intermediates **4a–h** have been cleanly and quantitatively prepared [R = C_3H_7, C_5H_{11}, C_7H_{15}, $C_{12}H_{25}$, CH_2=$CHCH_2$, CH_3CH=$CHCH_2$, $ClCH_2(CH_2)_2$, $ClCH_2(CH_2)_3$] (Scheme 1).

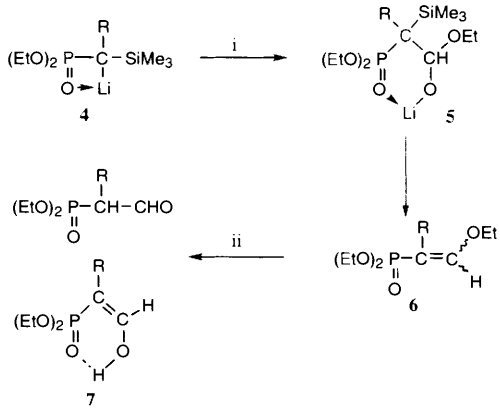


a R = Pr, X = I; **b** R = C_5H_{11}, X = I; **c** R = C_7H_{15}, X = I; **d** R = $C_{12}H_{25}$, X = I; **e** R = allyl, X = Br; **f** R = crotyl, X = Br; **g** R = $ClCH_2(CH_2)_2$, X = Br; **h** R = $ClCH_2(CH_2)_3$, X = Br.

Scheme 1 *Reagents and conditions:* i, BuLi (2.1 mol equiv.), $ClSiMe_3$ (1.1 mol equiv.), THF, −80 °C; ii, RX, THF, −30 °C; iii, BuLi (1.1 mol equiv.), THF, −80 °C

Results and discussion

We envisaged that the phosphorylated carbanions **4** could provide new intermediates in the synthesis of 1-formylalkylphosphonates **7**. Thus, on treatment of the carbanions **4** with ethyl formate, a Peterson-type reaction to afford two, *E* and *Z*, phosphorylated enol ethers was expected to occur[4] *via* the elimination of lithiated silanol, hydrolysis of the so formed enol ethers being achieved by treatment in acidic medium. Previous approaches to 1-formylalkyl phosphonates are based on the condensation of α-lithioalkylphosphonates with dimethylformamide but limited by both the availability of the nucleophile and the reactivity of the electrophile.[5] In this paper we describe the results of experiments that were realized (i) to identify the factors that control the formation of **7** and (ii) to demonstrate the feasibility of this new approach. Two routes have been examined and each of these will be described in turn. In the first route (Scheme 2), the carbanion **4a** (R = C_3H_7) taken as template, was treated with ethyl formate (1.1 equiv.) in THF at low temperature to give in quantitative yield the lithiated hemiacetal **5a**. This spontaneously decomposes to an isomeric mixture of the two expected phosphorylated enol ethers **6a** resulting from an exclusive Peterson-type reaction and easily identified by ^{31}P NMR analysis [δ_P(THF) +20 (*E*), (75%) and +25 (*Z*), (25%)]. However, these were not isolated but, rather intercepted by directly pouring the cold, crude product mixture into a cold biphasic mixture of hydrochloric acid (5 mol dm^{-3}) and dichloromethane (CH_2Cl_2). Upon stirring of the two phosphorylated enol ethers **6a** at 0 °C over 1 h the hydrolysis was complete and the corresponding 1-formylbutyl phosphonate **7a** was isolated in reasonable yield (55%) as a mixture of aldehyde [δ_P(THF) +23] and enol [δ_P(THF) +27.7] after purification by double extraction acid and base. When similar treatment was repeated but with the hydrolysis step being carried out with a more concentrated hydrochloric acid solution (12 mol dm^{-3}), **7a** was equally isolated in 55% yield.

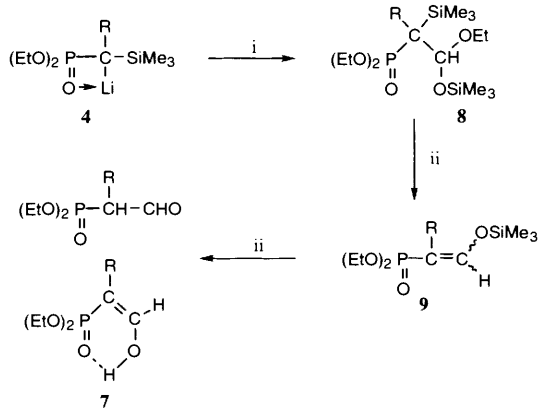


Scheme 2 *Reagents and conditions:* i, HCO_2Et (1.1 mol equiv.), THF, −80 °C; ii, HCl (5 mol dm^{-3})–CH_2Cl_2, −80 °C to 0 °C

However, when the cold mixture of the two enol ethers **6a** was heated to room temperature and treated at that temperature

with hydrochloric acid (5 mol dm^{-3}) the two enol ethers **6a** did not behave in the same way as previously: thus, since hydrolysis could not be driven to completion, it was not possible to isolate or purify the phosphorylated aldehyde **7a**. Attention was next turned to the use of the carbanions **4b** and **4e**, as starting materials for the synthesis of 1-formylalkylphosphonates **7b** and **7e**. The carbanions **4b** and **4e** reacted with ethyl formate to give the phosphorylated enol ethers **6b** and **6e**; finally, on acid hydrolysis, **6b** and **6e** behave in the same way as **6a** to afford 1-formylalkylphosphonates **7b** and **7e** in low overall yields (30 and 50%, respectively).

This first route being dependent on a balance of factors (steric, temperature, concentration, *etc*) which could not be easily overcome, a simple and efficient protocol for construction of 1-formylalkylphosphonates **7** has been developed using the formation of an intermediate mixed acetal **8**. In the second route (Scheme 3) we assumed that the hydrolysis of a phosphorylated mixed acetal **8**, more sensitive to acid hydrolysis than the phosphorylated enol ethers **6**, could provide a new and better approach to 1-formylalkylphosphonates **7**.



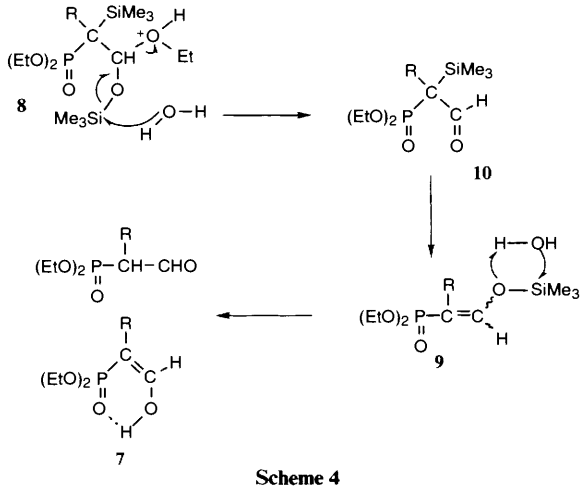
Scheme 3 *Reagents and conditions:* i, HCO_2Et (1.1 mol equiv.), $ClSiMe_3$ (1.5 mol equiv.), THF, −90 °C; ii, HCl (2 mol dm^{-3})–CH_2Cl_2, 20 °C, 60 min

Thus, to investigate this approach, the carbanion **4a** (R = C_3H_7) was allowed to react at low temperature (−90 °C) with ethyl formate (1.1 equiv.) in the presence of an excess of chlorotrimethylsilane (1.5 equiv.). On reaction the desired mixed acetal **8a** was obtained as the major product [δ_P(THF) +32.5 94%] with a small quantity of the enol ethers **6a** (6%). The reaction mixture was then allowed to return to room temperature when it was poured into a biphasic mixture of hydrochloric acid (2 mol dm^{-3}) and CH_2Cl_2. After 60 min at room temperature (as judged by ^{31}P NMR analysis) **8a** was completely hydrolysed to give a rather better overall yield of the aldehyde **7a** (73%) as a mixture of aldehyde [δ_P(THF–CH_2Cl_2). +22] and the enol [δ_P(THF–CH_2Cl_2) +27] after purification by double extraction acid and base.

The preference for the silylated enol ethers **9** in Scheme 3 was related to the ease of nucleophilic displacement at the $OSiMe_3$ ether group rather than the OEt ether group in the mixed acetal **8**. The proposal, which is illustrated in Scheme 4, for the hydrolysis of the phosphorylated mixed acetal **8** into the 1-formylalkylphosphonate **7**, would involve initial nucleophilic attack of the silyl group to generate the intermediate α-silylated α-substituted formyl phosphonate **10**. Given the α-position of the silyl group to the formyl group in **10**, [1,3]-rearrangement of **10** to deliver the transient silylated enol ether **9** becomes feasible, this one being more sensitive to acid hydrolysis than the corresponding ethoxy enol ether **6**.

This type of rearrangement has not been rigorously proven but it was suggested by both the oxophilic character of silicium and the enol form and it was considered to be the most reasonable explanation for the easy and complete hydrolysis of the mixed acetal **8**.

The preference for chlorotrimethylsilane as protecting group was confirmed after repeated reactions between the carbanion **4a** and other chlorosilanes. On reaction with chlorotriethylsilane three components were observed by ^{31}P NMR analysis; one of these was the mixed acetal [δ_P(THF) +32.4] in reasonable yield (41%) and two other signals were assigned to the enol ethers [δ_P(THF) +24.9 and +19.8]. With chlorotriisopropylsilane the corresponding mixed acetal was not detectable and the two enol ethers were the only products observed. The influence of the formylating agent has also been examined and, using dimethylformamide in association with chlorotrimethylsilane, formation of the corresponding mixed acetal was not detectable in the crude reaction mixture.



Scheme 4

Encouraged by these preliminary findings the synthesis of compounds **7** was explored in order to confirm the validity of the model reaction. The carbanions **4b–h** were prepared as described in Scheme 1 and in an analogous way were allowed to react with ethyl formate and chlorotrimethylsilane in excess (1.5 equiv.) at low temperature (−90 °C) in THF. The influence of the alkyl moiety has been examined using both a saturated and an unsaturated long chain. All were converted in quantitative yield into the desired mixed acetal **8** and on treatment in a biphasic acid system underwent rearrangement and complete hydrolysis to give 1-formylalkylphosphonates **7b–h** isolated in good yields (45–73%) after purification by double extraction acid and base. Thus a series of 1-formylalkylphosphonates **7a–h** were synthesized and characterized. Structures of products were confirmed by NMR (^1H, ^{31}P and ^{13}C) and mass spectrometry. In conclusion, this 'one-pot' procedure describes a new methodology for the synthesis of 1-formylalkylphosphonates based on the condensation of α-phosphorylated α-silylated α-substituted carbanion with ethyl formate in the presence of chlorotrimethylsilane. It is interesting to note that the reported successive exchange of the three chlorine atoms of diethyl trichloromethylphosphonate **1** was very selective. In fact, no side-products were detected, showing that the possible polysilylation and the lithium–chlorine exchange pathways were uncompetitive reactions under these experimental conditions. Further work in this area is being focused on exploiting and extending the synthetic utility of diethyl trichloromethylphosphonate.

Experimental

^{31}P NMR, ^1H NMR and ^{13}C NMR spectra were recorded on a Bruker AC 200 instrument with 85% H_3PO_4 as external

standard (positive chemical shifts are downfield of this reference) for ^{31}P NMR and $CDCl_3$ as internal standard for ^{1}H NMR and ^{13}C NMR; coupling constants are given in Hz. High-resolution mass spectra (HRMS) were recorded on VG ZAB-HSQ or Bruker CMS 47% ICR FT mass spectrometers. All reactions were carried out under an inert atmosphere and scrupulously anhydrous conditions. A Buchi GKR-50 apparatus with three flasks was used for distillation. The flask containing the crude product was in the upper part of the oven, and the collecting flask just outside.

General procedure for the synthesis of 1-formylalkylphosphonates 7a–h

Typical procedure for the synthesis of α-phosphorylated α-silylated α-substituted carbanions 4a–h. To a stirred mixture of a 1.6 mol dm^{-3} hexane solution of BuLi (53 cm^3, 84 mmol) and dry THF (100 cm^3) cooled to −80 °C were added dropwise trichloromethylphosphonate (10.2 g, 40 mmol) and $ClSiMe_3$ (4.8 g, 44 mmol) in THF (20 cm^3). Stirring was continued at −80 °C for about 15 min until formation of the carbanion **2** was complete, as indicated by ^{31}P NMR spectroscopy. The alkyl halide (RX) (44 mmol) in THF (10 cm^3) was added dropwise at −30 °C to the stirred mixture which was then allowed to warm to room temperature until formation of the phosphonate **3** was complete as proved by ^{31}P NMR spectroscopy. The mixture was cooled to −80 °C and a solution of BuLi in hexane (28 cm^3, 44 mmol) was added at this temperature. After a few minutes the carbanion **4** was obtained quantitatively.

***via* The enol ether route 7a.** Ethyl formate (3.3 g, 44 mmol) in THF (20 cm^3) was added dropwise at −80 °C to a solution of the carbanion **4** and the mixture was stirred for 15 min at this temperature: it was then poured into an ice-cold mixture of hydrochloric acid (5 mol dm^{-3} solution; 40 cm^3) and dichloromethane (40 cm^3) and stirred at this temperature for 60 min. The aqueous layer was extracted with dichloromethane (3 × 30 cm^3) and the combined extracts were washed with a solution of sodium hydroxide (2 mol dm^{-3} solution; 3 × 35 cm^3). The aqueous layers were separated, made acidic by treatment with hydrochloric acid (12 mol dm^{-3}) and then extracted with dichloromethane (3 × 30 cm^3). The combined extracts were washed with water (15 cm^3), dried ($MgSO_4$) and evaporated under reduced pressure to afford crude product which was purified by distillation under reduced pressure using a bulb-to-bulb apparatus.

***via* The mixed acetal route 7a–h.** A mixture of ethyl formate (3.3 g, 44 mmol) and chlorotrimethylsilane (6.5 g, 60 mmol) in THF (20 cm^3) were added dropwise to a solution of the carbanion **4** at −90 °C. The mixture was stirred for 15 min at this temperature and then allowed to warm to room temperature when it was poured into an ice-cold mixture of hydrochloric acid (2 mol dm^{-3} solution; 55 cm^3) and dichloromethane (40 cm^3) and stirred at this temperature for 60 min. The aqueous layer was extracted with dichloromethane (3 × 30 cm^3) and the combined extracts were washed with aqueous sodium hydroxide (2 mol dm^{-3} solution; 3 × 35 cm^3). The aqueous layers were separated, made acidic by treatment with hydrochloric acid (12 mol dm^{-3}) and then extracted with dichloromethane (3 × 30 cm^3). The combined extracts were separated, washed with water (15 cm^3), dried ($MgSO_4$) and evaporated under reduced pressure to afford crude product which was purified by distillation under reduced pressure using a bulb-to-bulb apparatus. The large temperature range is due to the distillation of a mixture of the keto–enol tautomers.

Diethyl 1-*formylbutylphosphonate* **7a**.—(73%), bp (20 mmHg) 175–190 °C; $\delta_P(CDCl_3)$ +23.17 and +27.76; $\delta_H(CDCl_3)$ 0.94 [t, $^3J_{H,H}$ 7, $CH_3(CH_2)_2$], 1.35 (t, $^3J_{H,H}$ 7, CH_3CH_2O), 1.9 [m, $CH_3(CH_2)_2$], 3 (dm, $^2J_{H,P}$ 26, PC*H*CHO), 4.16 (m, CH_3CH_2O) and 9.65 (d, $^3J_{H,H}$ 3, CHO); $\delta_C(CDCl_3)$ 13.9 [s, $CH_3(CH_2)_2$, aldehyde], 14.2 [s, $CH_3(CH_2)_2$, enol], 16.4 (d, $^3J_{C,P}$ 6.3, CH_3CH_2O, enol), 16.5 (d, $^3J_{C,P}$ 6, CH_3CH_2O, aldehyde), 21.7 (d, $J_{C,P}$ 13.7, CH_2, aldehyde), 22.1 (s, CH_2, enol), 25.8 (d, $J_{C,P}$ 4.6, CH_2, aldehyde), 26.1 (d, $J_{C,P}$ 6.5, CH_2, enol), 53.0 (d, $^1J_{C,P}$ 126.6, *C*HCHO), 61.5 (d, $^2J_{C,P}$ 5.6, CH_2O, enol), 63.1 (d, $^2J_{C,P}$ 7.5, CH_2O, aldehyde), 99.5 (d, $^1J_{C,P}$ 196.3, *C*=CHOH), 157.2 (d, $^2J_{C,P}$ 29.0, =CHOH), 196.3 (d, $^2J_{C,P}$ 4.5, CHO) (Found: M^+, 222.1020. Calc. for $C_9H_{19}O_4P$: *M*, 222.1020).

Diethyl 1-*formylhexylphosphonate* **7b**.—(73%), bp (20 mmHg) 185–200 °C; $\delta_P(CDCl_3)$ +22.47 and +27.40; $\delta_H(CDCl_3)$ 0.83 [t, $^3J_{H,H}$ 6.5, $(CH_2)_4CH_3$], 1.25 (dt, $^3J_{H,H}$ 7, CH_3CH_2O), 1.9 [m, $CH_3(CH_2)_3CH_2$], 2.9 (dm, $^2J_{H,P}$ 25, PC*H*CHO), 4.10 (m, CH_3CH_2O) and 9.65 (d, $^3J_{H,H}$ 3, CHO); $\delta_C(CDCl_3)$ 14.2 [s, $CH_3(CH_2)_4$], 16.6 (s, $^3J_{C,P}$ 6.8, CH_3CH_2O), 22.7 (s, CH_2, aldehyde), 22.9 (s, CH_2, enol), 24.2 (d, $J_{C,P}$ 6.3, CH_2, enol), 28.4 (d, $J_{C,P}$ 13.3, CH_2, aldehyde), 28.7 (s, CH_2, enol), 31.9 (s, CH_2, enol), 32.2 (s, CH_2, aldehyde), 53.5 (d, $^1J_{C,P}$ 126.6, *C*HCHO), 61.7 (d, $^2J_{C,P}$ 4.6, CH_2O, enol), 63.3 (d, $^2J_{C,P}$ 6.9, CH_2O, aldehyde), 99.8 (d, $^1J_{C,P}$ 195.6, *C*=CHOH), 157.4 (d, $^2J_{C,P}$ 29.2, =CHOH) and 196.8 (s, CHO) (Found: M^+, 250.1333. Calc. for $C_{11}H_{23}O_4P$: *M*, 250.1333).

Diethyl 1-*formyloctylphosphonate* **7c**.—(72%), bp (20 mmHg) 205–215 °C; $\delta_P(CDCl_3)$ +22.47 and +27.40; $\delta_H(CDCl_3)$ 0.81 [t, $^3J_{H,H}$ 6.4, $(CH_2)_4CH_3$], 1.28 (dt, $^3J_{H,H}$ 7, CH_3CH_2O), 1.9 [m, $CH_3(CH_2)_5CH_2$], 2.9 (dm, $^2J_{H,P}$ 25, PC*H*CHO), 4.10 (m, CH_3CH_2O) and 9.58 (d, $^3J_{H,H}$ 3, CHO); $\delta_C(CDCl_3)$ 14.2 [s, $CH_3(CH_2)_6$], 16.3 (d, $^3J_{C,P}$ 6.6, CH_3CH_2O, enol), 16.4 (d, $^3J_{C,P}$ 5.7, CH_3CH_2O, aldehyde), 22.7 (s, CH_2, aldehyde), 22.8 (s, CH_2, enol), 23.6 (d, $J_{C,P}$ 4.4, CH_2, aldehyde), 23.9 (d, $J_{C,P}$ 6.2, CH_2, enol), 28.4 (d, $J_{C,P}$ 13.4, CH_2, aldehyde), 28.8 (s, CH_2, enol), 29.0 (s, CH_2, aldehyde), 29.3 (s, CH_2, enol), 29.4 (s, CH_2, aldehyde), 29.7 (s, CH_2, enol), 31.8 (s, CH_2, aldehyde), 32.0 (s, CH_2, enol), 53.1 (d, $^1J_{C,P}$ 126.5, *C*HCHO), 61.3 (d, $^2J_{C,P}$ 4.7, CH_2O, enol), 62.9 (d, $^2J_{C,P}$ 6.7, CH_2O, aldehyde), 99.5 (d, $J_{C,P}$ 196.1, *C*=CHOH), 157.0 (d, $^2J_{C,P}$ 29.2, =CHOH). 196.1 (s, CHO) (Found: M^+, 278.1646. Calc. for $C_{13}H_{27}O_4P$: *M*, 278.1646).

Diethyl 1-*formyltridecylphosphonate* **7d**.—(69%), bp (20 mmHg) 210–225 °C; $\delta_H(CDCl_3)$ +22.76 and +28.45; $\delta_H(CDCl_3)$ 0.88 [t, $^3J_{H,H}$ 6.4, $(CH_2)_{11}CH_3$], 1.26 [m, CH_3CH_2O and $CH_3(CH_2)_{10}CH_2$], 1.9 [m, $CH_2(CH_2)_5CH_3$], 2.1 (m, $PCHCH_2$), 4.0 (m, CH_3CH_2O), 7.37 (d, $^3J_{H,H}$ 10.7, PC=C*H*OH), 9.60 (d, $^3J_{H,H}$ 3, CHO); $\delta_C(CDCl_3)$ 14.1 [s, $CH_3(CH_2)_{11}$], 16.2 (d, $^3J_{C,P}$ 5.9, CH_3CH_2O, aldehyde), 16.4 (d, $^3J_{C,P}$ 5.3, CH_3CH_2O, enol), 22.7 (s, CH_2), 23.5 (d, $J_{C,P}$ 4.5, CH_2, enol), 23.8 (d, $J_{C,P}$ 6.2, CH_2, aldehyde), 28.3 (d, $J_{C,P}$ 13.6, CH_2, enol), 28.9 (d, $J_{C,P}$ 22.1, CH_2, aldehyde), 29.3 (s, CH_2), 29.4 (s, CH_2), 29.6 (s, CH_2), 29.7 (s, CH_2), 32.0 (s, CH_2), 53.9 (d, $^1J_{C,P}$ 126.3, *C*HCHO), 60.9 (d, $^2J_{C,P}$ 5.0, CH_2O, aldehyde), 62.5 (d, $^2J_{C,P}$ 6.8, CH_2O, enol), 100.0 (d, $^1J_{C,P}$ 195.2. *C*=CHOH), 156.5 (d, $^2J_{C,P}$ 29.1 =CHOH) and 196.1 (d, $^2J_{C,P}$ 4.5, CHO) (Found: M^+, 348.2429. Calc. for $C_{18}H_{37}O_4P$: *M*, 348.2429).

Diethyl 1-*formylbut*-3-*enylphosphonate* **7e**.—(58%), bp (20 mmHg) 160–180 °C; $\delta_P(CDCl_3)$ +22.04 and +27.13; $\delta_H(CDCl_3)$ 1.29 (t, $^3J_{H,H}$ 7, CH_3CH_2O), 2.71 (m, $CH_2CH=CH_2$), 3.01 (dm, $^2J_{H,P}$ 26, PC*H*CHO), 4.11 (m, CH_3CH_2O), 5.0 (m, $CH_2CH=CH_2$), 5.73 (m, $CH_2CH=CH_2$), 9.60 (d, $^3J_{H,H}$ 2.5 CHO); $\delta_C(CDCl_3)$ 16.4 (d, $^3J_{C,P}$ 6.7, CH_3CH_2O, enol), 16.6 (d, $^2J_{C,P}$ 8.2, CH_3CH_2O, aldehyde), 28.0 (d, $^2J_{C,P}$ 3.8, $CH_2CH=$, aldehyde), 28.3 (d, $^2J_{C,P}$ 6.9, $CH_2CH=$, enol), 52.6 (d, $^1J_{C,P}$ 125.5, *C*HCHO), 61.7 (d, $^2J_{C,P}$ 4.5, CH_2O, enol). 63.4 (d, $^2J_{C,P}$ 6.9, CH_2O, aldehyde), 97.4 (d, $^1J_{C,P}$ 199.2, *C*=CHOH), 115.0 (s, $CH=CH_2$, enol), 117.7 (s, $CH=CH_2$, aldehyde), 134.5 (d, $^3J_{C,P}$ 14.1, $CH=CH_2$, aldehyde), 136.0 (s, $CH=CH_2$, enol), 157.8 (d, $^2J_{C,P}$ 28.9, =CHOH) and 195.9 (m, CHO) (Found: M^+, 220.0864. Calc. for $C_9H_{17}O_4P$: *M*, 220.0864).

Diethyl 1-*formylpent*-3-*enylphosphonate* **7f**.—(55%), bp (20 mmHg) 205–210 °C; $\delta_P(CDCl_3)$ +22.12 and +27.32;

$\delta_H(CDCl_3)$ 1.32 (t, $^3J_{H,H}$ 7, CH_3CH_2O), 1.61 (d, $^3J_{H,H}$ 6, $CH_3CH{=}CHCH_2$), 2.59 (m, $CH_3CH{=}CHCH_2$), 3.0 (dm, $^2J_{P,H}$ 26, $PCHCHO$), 4.19 (m, CH_3CH_2O), 5.38 (m, $CH_3CH{=}CHCH_2$), 5.49 (m, $CH_3CH{=}CHCH_2$), 9.60 (d, $^3J_{H,H}$ 3, CHO); $\delta_C(CDCl_3)$ 16.5 (d, $^3J_{C,P}$ 7.2, CH_3CH_2O, enol), 16.7 (d, $^3J_{C,P}$ 9.3, CH_3CH_2O, aldehyde), 18.1 (s, $CH_3CH{=}CH$), 27.2 (d, $^2J_{C,P}$ 6.1, $CH_2CH{=}CH$), 53.8 (d, $^1J_{C,P}$ 126.6, CHCHO), 61.8 (d, $^2J_{C,P}$ 4.1, CH_2O, enol), 63.3 (d, $^2J_{C,P}$ 6.7, CH_2O, aldehyde), 98.2 (d, $^1J_{C,P}$ 197.4, $C{=}CHOH$), 125.6 (s, $CH{=}CH_2$, enol), 127.1 (d, $^3J_{C,P}$ 13.9, $CH_2CH{=}$, aldehyde), 128.7 (s, $CH_2CH{=}$, enol), 134.5 (d, $^3J_{C,P}$ 14.1, $CH{=}CH_2$, aldehyde), 136.0 (s, $CH{=}CH_2$, enol), 157.6 (d, $^2J_{C,P}$ 30.2, $=CHOH$) and 196.4 (m, CHO) (Found: M^+, 234.1029. Calc. for $C_{10}H_{19}O_4P$: M, 234.1029).

Diethyl 4-chloro-1-formylbutylphosphonate **7g**.—(45%), bp (20 mmHg) 190–205 °C: $\delta_P(CDCl_3)$ +22.58 and +27.55; $\delta_H(CDCl_3)$ 1.2 (t, $^3J_{H,H}$ 7, CH_3CH_2O), 1.85 (m, $CH_2CH_2CH_2Cl$), 2.1 (m, $PCCH_2$), 3.73 (t, $^3J_{H,H}$ 2.4, $CH_2CH_2CH_2Cl$), 4.03 (m, CH_3CH_2O) and 7.15 (d, $^3J_{H,H}$ 10.8, $PC{=}CHOH$) (Found: M^+, 256.0632. Calc. for $C_9H_{18}ClO_4P$: M, 256.0631).

Diethyl 5-chloro-1-formylpentylphosphonate **7h**.—(50%), bp (20 mmHg) 225–240 °C: $\delta_P(CDCl_3)$ +22.22 and +27.73; $\delta_H(CDCl_3)$ 1.3 (t, $^3J_{H,H}$ 7, CH_3CH_2O), 1.45–2.20 [m, $(CH_2)_3$], 2.95 (m, $PCHCHO$), 3.49 [t, $^3J_{H,H}$ 2.3, $CH_2(CH_2)_2CH_2Cl$], 4.13 (m, $^3J_{H,H}$ and $^3J_{H,P}$ 7, CH_3CH_2O), 7.33 (d, $^3J_{H,H}$ 10.5, $PC{=}CHOH$) and 9.63 (d, $^3J_{H,P}$ 2.66, $PCHCHO$); $\delta_C(CDCl_3)$ 16.3 (d, $^3J_{C,P}$ 6.5, CH_3CH_2O, enol), 16.4 (d, $^3J_{C,P}$ 5.4, CH_3CH_2O, aldehyde), 22.7 (s, CH_2, enol), 22.8 (s, CH_2, aldehyde), 25.7 (s, CH_2, aldehyde), 25.8 (s, CH_2, enol), 32.2 (s, CH_2, aldehyde and enol), 44.4 (s, CH_2Cl, aldehyde), 44.9 (s, CH_2Cl, enol), 52.9 (d, $^1J_{C,P}$ 126.6, CH_2CHO), 61.5 (d, $^2J_{C,P}$ 4.9, CH_3CH_2O, enol), 63.0 (d, $^2J_{C,P}$ 6.8, CH_3CH_2O, aldehyde), 98.9 (d, $^1J_{C,P}$ 197.3, $C{=}CHOH$), 157.1 (d, $^2J_{C,P}$ 28.7, $C{=}CHOH$) and 195.8 (d, $^2J_{C,P}$ 3.6, CHO) (Found: M^+, 270.0787. Calc. for $C_{10}H_{20}ClO_4P$: M, 270.0787).

Acknowledgements

We thank Dr J. P. Morizur (Université Paris VI, ERS 72 CNRS) for the HRMS measurements.

References

1 G. M. Kosolapoff, *J. Am. Chem. Soc.*, 1947, **69**, 1002.
2 (*a*) D. Seyferth and R. S. Marmor, *J. Organomet. Chem.*, 1973, **59**, 237; (*b*) J. F. Normant, P. Perriot and J. Villieras, *Synthesis*, 1975, 458; (*c*) P. Coutrot, C. Laurenco, J. F. Normant, P. Perriot, P. Savignac and J. Villieras, *Synthesis*, 1977, 615; (*d*) J. Villieras, A. Reliquet and J. F. Normant, *Synthesis*, 1978, 27; (*e*) J. Villieras, P. Perriot and J. F. Normant, *Synthesis*, 1978, 29; (*f*) J. Villieras, P. Perriot and J. F. Normant, *Synthesis*, 1978, 31; (*g*) P. Perriot, J. Villieras and J. F. Normant, *Synthesis*, 1978, 33; (*h*) G. T. Lowen and M. R. Almond, *J. Org. Chem.*, 1994, **59**, 4548.
3 C. Grandin, N. Collignon and P. Savignac, *Synthesis*, 1995, 239.
4 (*a*) D. J. Peterson, *J. Org. Chem.* 1968, **33**, 780; (*b*) F. A. Carey and A. S. Court, *J. Org. Chem.*, 1972, **37**, 939; (*c*) C. Trindle, J. T. Hwang and F. A. Carey, *J. Org. Chem.*, 1973, **38**, 2664; (*d*) D. J. Ager, *Synthesis*, 1984, 384; (*e*) E. E. Aboujaoude, S. Lietje, N. Collignon, M. P. Teulade and P. Savignac, *Synthesis*, 1986, 934; (*f*) M. P. Teulade and P. Savignac, *J. Organomet. Chem.*, 1988, **338**, 295.
5 (*a*) E. E. Aboujaoude, N. Collignon and P. Savignac, *Synthesis*, 1983, 634; (*b*) G. A. Olah, L. Ohannesian and M. Arvanaghi, *J. Org. Chem.*, 1984, **49**, 3856; (*c*) P. Savignac and C. Patois, *Org. Synth.*, 1994, **72**, 241.

Paper 5/04034E
Received 22*nd June* 1995
Accepted 21*st July* 1995