The Phosphorylation of Organic Compounds by Phosphoric Anhydride. Part 3.[1] Synthesis of Monosubstituted Ketenes in the Reaction of Esters with Phosphoric Anhydride and Cyclotrimerization of these Ketenes

Dimitry A. Efremov,†[a] Pavel M. Zavlin,[b] Nataly S. Essentseva[b] and John C. Tebby*[a]
[a] Staffordshire University, Stoke-on-Trent ST4 2DE, UK
[b] St Petersburg Institute of Cinema and Television, 191126 St Petersburg, ul. Pravdi, 13, Russia

Monosubstituted ketenes 1 have been synthesized from substituted acetic esters 2 by elimination of alcohol under the action of phosphoric anhydride. The ketenes undergo cyclotrimerization to give substituted phloroglucinols (1,3,5-trihydroxybenzenes) 3 and their phosphorylated derivatives.

The synthesis of various functionalized aromatic compounds from structural blocks that contain different functional groups is of considerable synthetic importance. This procedure possesses a number of advantages[2] over electrophilic substitution of arenes. For example, it is possible to synthesize directly aryl compounds bearing substituents in orientations which contradict the normal directing rules governing electrophilic substitution. Such an approach also lends itself to the synthesis of highly substituted derivatives. As a consequence the synthesis of substituted benzenes from non-cyclic precursors is a developing branch of organic chemistry.[2] Surprisingly, there are few publications devoted to the preparation of highly functionalized aromatic compounds from structural blocks such as monofunctionalized ketenes 1. These intermediates are available from monosubstituted acetic esters 2 and provide the unique possibility of the direct synthesis of phloroglucinols 3 ($X^1 = X^2 = X^3 = H$). It is probable that the preparation of 2,4,6-tris(ethoxycarbonyl)phloroglucinol 3 ($X^1 = X^2 = X^3 = H$, $Z = CO_2Et$)[3] from malonic ester and 2,4,6-triethylphloroglucinol 3 ($X^1 = X^2 = X^3 = H$, $Z = Et$)[4] from propanoyl chloride involved the generation of intermediate monosubstituted ketenes. The generation and chemical properties of ketenes have been well studied[5] and typical reactions of ketenes include dimerization and cycloaddition, especially for those which are activated by highly polarizing substituents. Dimerization and cycloaddition of ketenes take place under conditions that are also suitable for cyclotrimerization. The cyclotrimerization of disubstituted ketenes has been described.[6,7] Thus, Erikson[6] showed that dimethylketene is converted into hexamethylcyclohexane-1,3,5-trione in boiling toluene under the action of sodium methanoate. Hexaphenylcyclohexane-1,3,5-trione has also been prepared from diphenylketene.[7] Such cyclotrimerization cannot produce aromatic systems because geminal substituents prevent enolization. Both reactions are accompanied by the formation of the corresponding dimers such as the cyclobutane-1,3-dione 5.

The current paper describes a simple and convenient method for the synthesis of monofunctionalized ketenes by the reaction of substituted alkylacetic esters 2a–g with phosphoric anhydride and the cyclotrimerization of those ketenes to produce highly substituted benzenes (Scheme 1). The arenes can be synthesized in one-pot reactions which involve heating the reactants without a solvent. The esters 2d, f and g, which possess highly electronegative groups, react vigorously with phosphoric anhydride whereas the others need prolonged heating to produce the monosubstituted ketenes 1a–e.
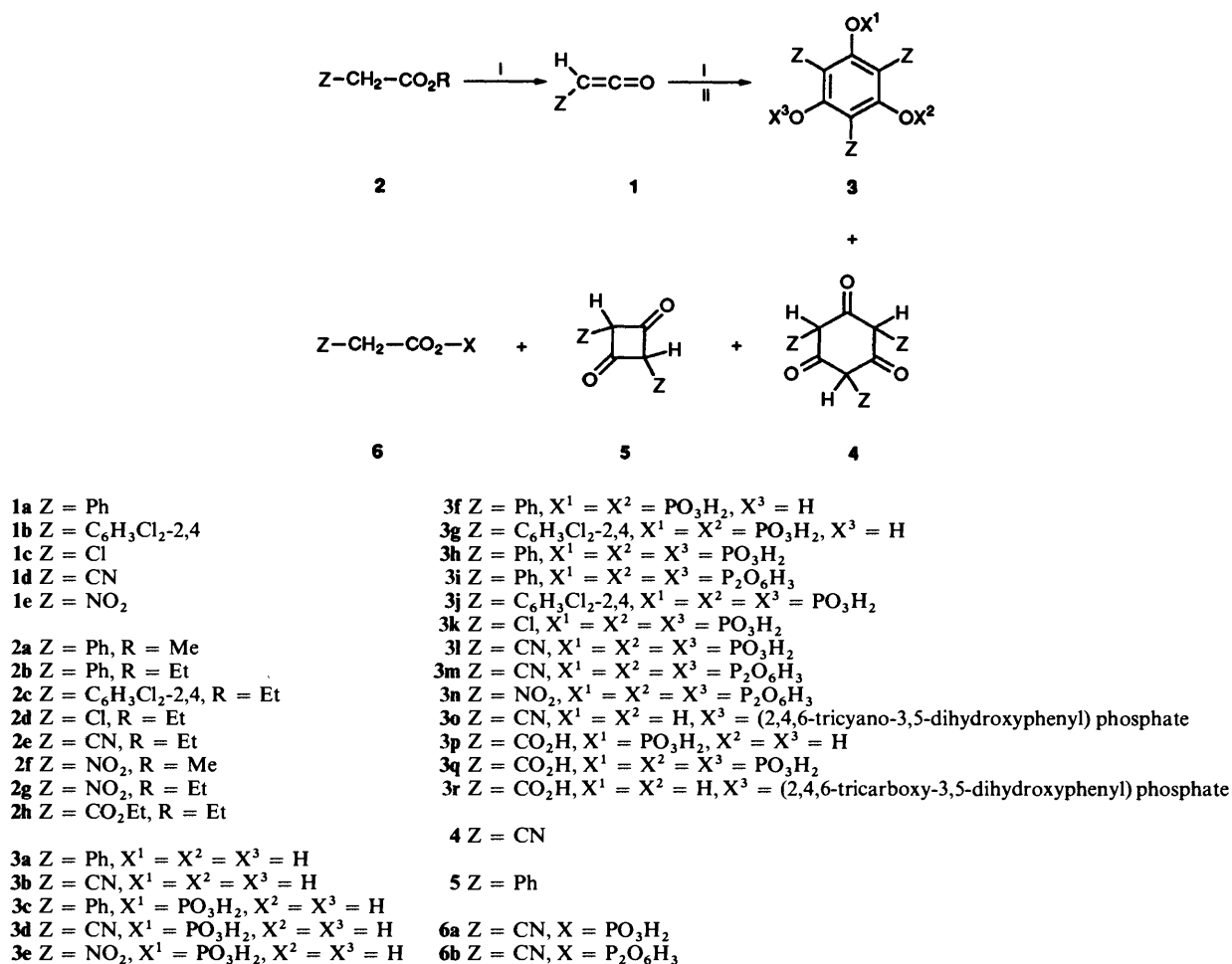
De-alcoholysis of the diethyl ester of malonic acid under the action of phosphoric anhydride was first described by Diels and Wolf[8] in 1906. The product (Scheme 2) was carbon suboxide which was produced in very low yield. Improved yields were obtained when the method was extended to the dimethyl, diphenyl and dibenzyl esters of malonic acid.[9] The highest yield of carbon suboxide was 25%.[10] The solid residue of the reaction mixture was not investigated. The chemical properties of carbon suboxide were the subject of a review[11] in 1974.

A recent study[12] of the reaction of carbon suboxide with anions in the gas phase showed that the primary centre of the nucleophilic attack is the carbonyl carbon atom, which led the authors to consider carbon suboxide as a vinyl analogue of carbon dioxide.[12]

Difunctionalized ketenes have been generated in situ by various processes mainly involving the decomposition of rather complicated, poorly accessible compounds. Moore and co-workers[13-15] reported several synthetic approaches to chloro-(bromo-, iodo-) cyanoketene by thermolysis of azidoquinones[13,14] or azidooxodihydrofuranones.[14,15] Dichloroketene was prepared from trichloroacetyl chloride and zinc.[16,17] There is only one example of the use of phosphoric anhydride for the preparation of a difunctionalized ketene[18] and that involved the conversion of fluorosulfonyl-β,β,β-trifluoropropanoic acid into ketene (Scheme 3). IR spectroscopy of an argon matrix,[17] NMR[19] and structural data[16,20] for the disubstituted ketenes and some of the monosubstituted ketenes have been reported. The de-alcoholysis of acetic esters by phosphoric anhydride has not been studied.

Cyanoketene 1d was prepared and isolated for the first time by treatment of cyanoacetic ester with phosphoric anhydride.[21] The ketene is a colourless liquid with b.p. −34 °C. It is not highly reactive and can be stored for long periods in cold diethyl ether solution. The ^{1}H NMR spectrum of ketene 1d contains one signal at δ 5.28 ppm and its ^{13}C NMR spectrum consists of three broad singlets at δ 52.2, 118.4 and 208.7 ppm. Cyanoketene 1d reacted with water, alcohols and amines to give cyanoacetic acid and its ester and amide derivatives, respectively. The chloroketene 1c and nitroketene 1e from the corresponding reactions of esters 2d and 2f, g with phosphoric anhydride were also trapped using liquid nitrogen, but they were too unstable either neat or in dilute solutions to be able to measure their spectra. However, passing the gaseous chloro- and nitro-ketenes 1c, e, which evolve from the reaction mixture, into cold water or alcohols gave the corresponding acetic acids or esters.[22,23] Titration of the aqueous solutions of the monosubstituted acetic acids made it possible to establish the yields of the monosubstituted ketenes 1c–e. The reactions of the ketenes 1c, e with amines were unsuccessful because the parent esters 2d, f and g and phosphoric anhydride reacted with
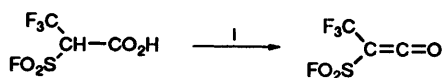

$$Z-CH_2-CO_2R \xrightarrow{\text{i}} \underset{Z}{\overset{H}{\diagdown}}C=C=O \xrightarrow{\text{i}}{\text{ii}} \text{3}$$

2   1   3

+

$$Z-CH_2-CO_2-X \quad + \quad \text{6} \quad + \quad \text{5} \quad + \quad \text{4}$$

6   5   4

1a Z = Ph	3f Z = Ph, X^1 = X^2 = PO_3H_2, X^3 = H
1b Z = $C_6H_3Cl_2$-2,4	3g Z = $C_6H_3Cl_2$-2,4, X^1 = X^2 = PO_3H_2, X^3 = H
1c Z = Cl	3h Z = Ph, X^1 = X^2 = X^3 = PO_3H_2
1d Z = CN	3i Z = Ph, X^1 = X^2 = X^3 = $P_2O_6H_3$
1e Z = NO_2	3j Z = $C_6H_3Cl_2$-2,4, X^1 = X^2 = X^3 = PO_3H_2
	3k Z = Cl, X^1 = X^2 = X^3 = PO_3H_2
2a Z = Ph, R = Me	3l Z = CN, X^1 = X^2 = X^3 = PO_3H_2
2b Z = Ph, R = Et	3m Z = CN, X^1 = X^2 = X^3 = $P_2O_6H_3$
2c Z = $C_6H_3Cl_2$-2,4, R = Et	3n Z = NO_2, X^1 = X^2 = X^3 = $P_2O_6H_3$
2d Z = Cl, R = Et	3o Z = CN, X^1 = X^2 = H, X^3 = (2,4,6-tricyano-3,5-dihydroxyphenyl) phosphate
2e Z = CN, R = Et	3p Z = CO_2H, X^1 = PO_3H_2, X^2 = X^3 = H
2f Z = NO_2, R = Me	3q Z = CO_2H, X^1 = X^2 = X^3 = PO_3H_2
2g Z = NO_2, R = Et	3r Z = CO_2H, X^1 = X^2 = H, X^3 = (2,4,6-tricarboxy-3,5-dihydroxyphenyl) phosphate
2h Z = CO_2Et, R = Et	
	4 Z = CN
3a Z = Ph, X^1 = X^2 = X^3 = H	
3b Z = CN, X^1 = X^2 = X^3 = H	5 Z = Ph
3c Z = Ph, X^1 = PO_3H_2, X^2 = X^3 = H	
3d Z = CN, X^1 = PO_3H_2, X^2 = X^3 = H	6a Z = CN, X = PO_3H_2
3e Z = NO_2, X^1 = PO_3H_2, X^2 = X^3 = H	6b Z = CN, X = $P_2O_6H_3$

Scheme 1   Reaction of phosphoric anhydride and monosubstituted acetic esters. *Reagents:* i, P_4O_{10}; ii, H_2O.

$$EtO_2C-CH_2-CO_2Et \xrightarrow[-2\,EtOH]{\text{i}} O=C=C=C=O$$

2h   carbon suboxide

3 p – r
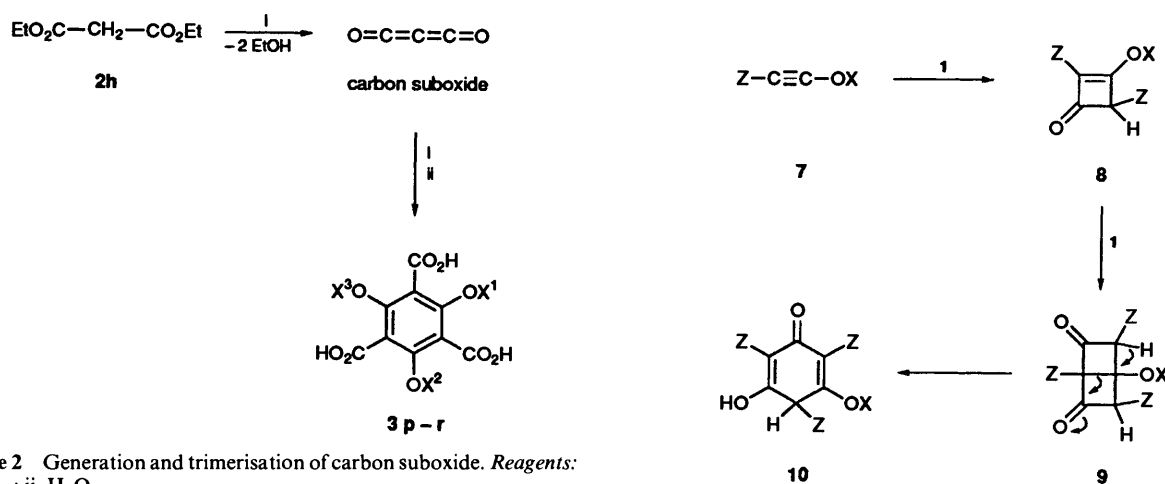
Scheme 2   Generation and trimerisation of carbon suboxide. *Reagents:* i, P_4O_{10}; ii, H_2O.

$$\underset{FO_2S}{\overset{F_3C}{\diagdown}}CH-CO_2H \xrightarrow{\text{i}} \underset{FO_2S}{\overset{F_3C}{\diagdown}}C=C=O$$

Scheme 3   Preparation of disubstituted ketene using phosphoric anhydride. *Reagent:* i, P_4O_{10}.

the liberation of a substantial quantity of carbon dioxide, which combined with the amines. Separation of the components of the solid residue of the reaction mixtures led to the isolation of a number of phloroglucinol derivatives 3. These compounds can be considered as the trimeric products of the reactions of

$$Z-C\equiv C-OX \xrightarrow{1} \text{8}$$

7   8

10   9

Scheme 4   Proposed reaction pathway for the trimerisation of ketenes by phosphoric anhydride

ketenes **1a–e** which have been phosphorylated by the excess of phosphoric anhydride and/or by polyphosphates formed in the de-alcoholysis of esters **2a–g**.

The common step of nearly all these reactions is cyclo-trimerization of ketenes to give hexasubstituted benzenes, *i.e.* phloroglucinol and its derivatives (Scheme 1). Four other compounds were also isolated from certain esters. These compounds have been shown to be a mixed anhydride of acetic acid and phosphoric acid **6a** (X = PO_3H_2; Z = CN) as well as

Table 1 Characteristic IR wavenumbers, v_{max}/cm^{-1}

Compound	Z	v_{OH} (C=O)	v_Z	v_{P-O}	v_{P-O-C}	v_{P-O-P}
6a	CN	3360 (1710)	2285	1270	1035	
6b	CN	3360	2285	1240	1010	960
5	Ph		1690			
4	CN	(1680)	1960			
3a	Ph	3450	1660			
3c	Ph	3420	1580	1225	1000	
3d	CN	3170	2195	1250	1020	
3e	NO₂	3030	1520 1325	1240	1040	
3f	Ph	3450	1600	1220	1005	
3g	$C_6H_3Cl_2$	3480	1560	1235	1090	
3h	Ph	3490	1560	1220	1030	
3i	Ph	3460	1600	1225	1045	970
3j	$C_6H_3Cl_2$	3480	1550	1240	1085	
3k	Cl	3045	760	1220	1050	
3l	CN	3060	2260	1240	1035	
3m	CN	3020	2265	1250	1030	925
3n	NO₂	3030	1560 1330	1230	1040	
3o	CN	3000	2270	1245	1075	
3p	CO₂H	3450	1710	1220	1030	
3q	CO₂H	3150	1710	1225	990	
3r	CO₂H	3200	1730	1210	980	

the pyrophosphoric acid **6b** (X = $P_2O_6H_3$; Z = CN), the disubstituted cyclobutane-1,3-dione **5** (Z = Ph) and trisubstituted cyclohexane-1,3,5-trione **4** (Z = CN). Their formation provides some evidence on the probable principal reaction pathways of the ketenes **1a–e**.

The first step of the reaction involves the formation of a ketene. This is substantiated by the detection and isolation of ketenes and their conversion into dimeric and trimeric products. The formation of the trimeric products may involve a dimeric intermediate or, alternatively, the solid phosphoric anhydride may act as a matrix to bring three molecules of ketene together. This latter possibility was inferred by the observation that when solid phosphoric anhydride was replaced by polyphosphoric acid no trimeric compounds were formed. The first proposed pathway involves *O*-phosphorylation of the ketenes (Scheme 4). Since it has been shown that ketenes rearrange reversibly to hydroxyacetylenes **7** (X = H) it is mechanistically reasonable to expect the initial intermediate to be the phosphorylated hydroxyacetylene **7**, in which the groups X are residual polyphosphates from the phosphoric anhydride. This is supported by the isolation of the mixed anhydride **6a** (X = PO_3H_2; Z = CN) which could arise from hydration of the triple bond of the ynol polyphosphate **7** with further hydrolysis of the polyphosphate fragment. When the substituent Z is a powerful electron acceptor the acetylene **7** will be strongly polarized and it is expected that it will be quite reactive towards the ketene. On the basis of the known reactivity of ketenes such a reaction would be expected to give the phosphorylated cyclobutenone **8**. A further cycloaddition of the phosphorylated cyclobutanone with ketene would give the bicyclohexane **9**. The relief of the strain of the endocyclic double bond in the cyclobutenone would be expected to be part of the driving force for this step. Prototropic rearrangement of the bicyclohexane **9** with cleavage of the bridging bond would lead to further stabilization and the generation of the cyclohexadieneone **10**, the keto tautomer of which is one of the products isolated. Phosphorylation or hydrolysis of this compound (with appropriate tautomerization) leads to all of the observed trimeric products. However, it should be noted that the β-keto-enol phosphate **10** would need to be much more susceptible to hydrolysis than the phenyl phosphates in order to

explain the production of the non-phosphorylated product. This would not be unexpected due to the formation of a highly delocalized enolate. If this occurs then the cyclobutanedione **5** isolated from the reactions could also arise from hydrolysis of the cyclobutenone intermediate **8**, as well as via direct dimerization of the ketene. Dimeric and trimeric structures of the compounds **3a, b, 4** and **5** have been proved by mass spectroscopy. Phenylketenes **1a, b** (Z = Ph, $C_6H_3Cl_2$) were not isolated in free state, probably because of their higher molecular weight and lower volatility.

The components of the reaction mixture residues were separated and isolated by their extraction with a sequence of solvents in accordance with the eluotropic series[24] followed by trituration, fractional crystallization and/or fractional recrystallization. Cyclohexanetrione **4** and the phloroglucinols **3a, b** were very soluble in non-polar solvents (hexane, tetrachloromethane, trichloromethane), whereas mixed anhydrides **6** and cyclobutanedione **5** were soluble in acetone, or mixtures of acetone with diethyl ether, or alcohols. Phosphorylated phloroglucinols **3c–o** were extracted from the reaction mixtures by repeated extractions with alcohols, ethyl acetate or their mixtures with water. The very poor solubility of the latter compounds made it possible to measure their NMR and IR spectra (Table 1) in the solid state only. The combined yield of the isolated products of the reaction of cyanoacetic ester **2e** with phosphoric anhydride was nearly quantitative (calculated for the ester) whereas for the other esters **2a–d, f, g** the total yields were lower (Table 2). All reactions gave an insoluble residue which appeared to be mainly polyphosphate and organic polymers from the ketenes and the products of their decarboxylation. Molecular mechanic modelling indicated that the relatively high yield of tricyanophloroglucinol **3b** may be due to the formation of an exceptionally stable association between the cyanoketene **1d** and phosphoric anhydride. Calculations with the COSMIC DOCKING program showed that the molecules of ketenes can be orientated along the P–O bonds of phosphoric anhydride; the distances between $C_α$ and O(P) are 3.338 ± 0.3115 Å, $C_β$ and P 3.271 ± 0.1899. Thus, across the series of ketenes the closest intermolecular distance was calculated for cyanoketene **1e** and phosphoric anhydride.

Table 2 The conditions of the reaction of monosubstituted ethanoic esters 2a–g with phosphoric anhydride, the types of the products formed and the yields of the products

Ester	Molecular ratio P_4O_{10}:ester	Temp. (°C)	Time (min)	Products (% Yield)
2a	1:2	190	60	3h (53), 3i (14)
2b	1:1.5	100	35	5 (26), 3a (19)
2b	1:2	190	60	3h (69)
2b	1:3.5	130	30	3c (27), 3h (32)
2b	1:3.5	130	45	3f (22), 3i (31)
2c	1:2	130	50	3j (64)
2c	1:3	130	55	3j (52)
2d	1:2	180	20	1c (12), 3k (40)
2d	1:3	180	25	1c (17), 3k (28)
2e	1:1.5	90	30	1d (19), 6a (8), 6b (6), 4 (17), 3a (25), 3l (9), 3m (12)
2e	1:3	90	35	1d (33), 4 (15), 3a (12), 3l (14), 3m (10)
2e	1:4	90	40	1d (26), 3d (36)
2e	1:4	125	45	1d (14), 3o (57)
2f	1:2	120	25	1e (15), 3e (28)
2f	1:2	180	45	1e (8), 3n (25)
2g	1:2	120	30	1e (12), 3e (33)
2h	1:4	130	35	3p (38), 3q (15), 3r (8)

The nature and relative proportions of the products obtained from the reaction of esters 2 with phosphoric anhydride depended upon the reaction conditions and, especially, the ratio of the reagents, the reaction temperature and reaction time (Table 2). The highly electronegative functional groups appeared to favour the process of phosphorylation of the phloroglucinols 3. In most cases a decrease of the proportion of ester relative to phosphoric anhydride, increased the yields of phosphorylated phloroglucinols. A higher temperature and longer reaction time favoured the formation of pyrophosphates of phloroglucinols, which is consistent with the earlier observations[25] that pyrophosphates may be produced through the phosphorylation of phosphates by phosphoric anhydride.

The reaction of diethyl malonic ester 2h (Z = CO_2Et; R = Et) and phosphoric anhydride proceeded in a similar way and formed the cyclic trimer which upon work-up and isolation gave acids 3p–r.

The ^{13}C NMR spectra showed that 2,4,6-tricyanocyclohexane-1,3,5-trione 4 (Z = CN) and 2,4,6-tricyanophloroglucinol 3b exist as an equilibrium mixture. Phloroglucinol 3b is dominant in polar solvents (acetone, DMSO, alcohols), δ_C 127.90 (COH) ppm in DMSO, whereas its tautomer 4 (Z = CN) prevails in non-polar solvents (benzene, tetrachloromethane, trichloromethane), δ_C 157.07 (C=O) ppm in CCl_4. Crystallization of either form 4 (Z = CN) or 3b gave crystals of mixed composition [δ_C 127.01 (COH) and 152.42 (C=O) ppm]. As expected, their UV spectra were also very sensitive to the position of the keto–enol equilibrium.

4   3b
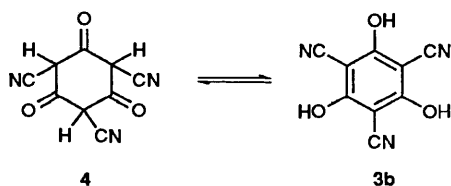
Experimental

IR spectra were determined as KBr discs, except for compounds 4 and 5 which were recorded as solutions in tetrachloromethane, on Pye Unicam SP3-200 and UR-20 instruments. NMR spectra were determined on JEOL FX90Q, Tesla BS-487C and Bruker 100 CXP instruments (the latter being used for the solid state studies) and the products were dissolved in the solvents shown. Mass spectra were measured with a Kratos MS80 spectrometer.

MM calculations were performed using COSMIC-90 program[26] in which non-bonded van der Waals energies were calculated using a two-parameter Morse curve and the van der Waals radius of hydrogen has been increased to 1.595 Å thus giving an H–H potential similar to that found in MM3. The MM modelling procedure was as follows. Partial atomic charges were calculated using the recently modified Liverpool 2 method.[27] Each structure was then optimized by a sequence of energy minimization methods. The DOCKING procedure involved was made by placing the molecules of ketenes on a 10 Å radius sphere about a phosphoric anhydride molecule followed by a conformational hunt and minimization of energies. The distances between the corresponding atoms in phosphoric anhydride and a ketene were measured for the docked system with the lowest potential energy of the 204 final positions.

Reaction of Esters 2a–h *with Phosphoric Anhydride.*—The normal procedure[28] involved heating a heterogeneous mixture of the appropriate ester and phosphoric anhydride (see Table 2). For the esters 2d, f and g heating was necessary only to start the reaction and then the exothermic reaction was controlled at the temperatures given in Table 2 using a water bath. The reactions were accompanied by a violent evolution of gases which lasted for 20–45 min. The gaseous products were either isolated using a liquid nitrogen trap or directed into a flask containing an appropriate reagent (water, alcohols, amines). By the end of the process the residual reaction mixture was a very

dark porous solid. After cooling, the residue was treated with water and then left for 10–12 h. The solid reaction residue was treated consecutively with a series of solvents that extracted the various products. After fractional crystallization from these solvents or/and trituration and/or recrystallization the corresponding products were isolated. The reaction conditions and yields are given in Table 2.

2,4,6-Triphenylbenzene-1,3,5-triol **3a**. The solid residue from the reaction of ester **2b** and phosphoric anhydride as described above was extracted with trichloromethane. Fractional crystallization from trichloromethane gave a violet solid, m.p. 78–80 °C; δ_C 116.84–124.55 (Ar) and 149.05 (COH); m/z 357 (M$^+$) (Found: C, 81; H, 4.9. $C_{24}H_{18}O_3$ requires C, 81.35; H, 5.08%).

2,4-Diphenylcyclobutane-1,3-dione **5**. The residue from the previous extraction was re-extracted with diethyl ether–acetone (50:50 v/v). Fractional crystallization from the solvent mixture gave a yellow solid, m.p. 156–157 °C; δ_C 29.90 (CH), 118.75–122.83 (Ph) and 188.10 (C=O); m/z 226 (M$^+$) (Found: C, 81.1; H, 4.8. $C_{16}H_{12}O_2$ requires C, 81.35; H, 5.08%).

3,5-Dihydroxy-2,4,6-triphenylphenyl dihydrogen phosphate **3c**. The residue from the previous extraction was re-extracted with acetone. Fractional crystallization from acetone gave a russet solid, m.p. 64–65 °C; δ_C 119.76–126.63 (Ar), 142.12 (COP) and 146.21 (COH); δ_P −3.87 (Found: C, 66.2; H, 4.2; P, 8.5. $C_{24}H_{19}O_6P$ requires C, 66.35; H, 4.37; P, 8.29%).

(5-Hydroxy-2,4,6-triphenyl)-1,3-phenylene bis(dihydrogen phosphate) **3f**. The residue from the previous extraction was re-extracted with acetone–ethanol (60:40 v/v). Fractional crystallization from the solvent mixture gave a brown solid, m.p. 75–76 °C; δ_C 117.36–123.15 (Ar), 144.81 (COP) and 147.95 (COH); δ_P −3.19 (Found: C, 55.7; H, 3.7; P, 12.5. $C_{24}H_{20}O_9P_2$ requires C, 56.03; H, 3.89; P, 12.62%).

2,4,6-Triphenylbenzene-1,3,5-triyl tris(dihydrogen phosphate) **3h**. The residue from the previous extraction was re-extracted with ethanol. Fractional crystallization from ethanol gave a dark brown solid, m.p. 146–148 °C; δ_C 119.15–124.47 (Ar) and 143.70 (COP); δ_P −2.64 (Found: C, 48.2; H, 3.2; P, 15.9. $C_{24}H_{21}O_{12}P_3$ requires C, 48.48; H, 3.53; P, 15.65%).

2,4,6-Triphenylbenzene-1,3,5-triyl tris(trihydrogen pyrophosphate) **3i**. The residue of the previous extraction was re-extracted with methanol. Fractional crystallization from methanol gave a brown–black solid, m.p. 48–52 °C; δ_C 116.65–123.02 (Ar) and 139.40 (COP); δ_P −9.78 and −2.23 (Found: C, 34.2; H, 2.5; P, 23.0. $C_{24}H_{24}O_{12}P_6$ requires C, 34.53; H, 2.87; P, 22.35%).

5-Hydroxy-2,4,6-tris(2,4-dichlorophenyl)-1,3-phenylene bis-(dihydrogen phosphate) **3g**. The solid residue from the reaction of ester **2c** and phosphoric anhydride as described above was extracted with ethanol. Fractional crystallization from ethanol gave a dark yellow solid, m.p. 72–73 °C; δ_C 119.89–127.25 (Ar) and 136.58 (COP); δ_P −2.62 (Found: C, 39.8; H, 2.1; P, 8.4. $C_{24}H_{14}Cl_6O_9P_2$ requires C, 39.94; H, 1.94; P, 8.59%).

2,4,6-Tris(2,4-dichlorophenyl)benzene-1,3,5-triyl tris(dihydrogen phosphate) **3j**. The solid residue from the previous extraction was re-extracted with ethyl acetate. Fractional crystallization from ethyl acetate gave a grey solid, m.p. 77–78 °C; δ_C 118.96–125.90 (Ar) and 139.75 (COP); δ_P −1.39 (Found: C, 35.8; H, 2.1; P, 11.2. $C_{24}H_{15}Cl_6O_{12}P_3$ requires C, 35.95; H, 1.87; P, 11.60%).

2,4,6-Trichlorobenzene-1,3,5-triyl tris(dihydrogen phosphate) **3k**. The solid residue from the reaction of ester **2c** and phosphoric anhydride as described above was extracted with methanol. Fractional crystallization from methanol gave a black solid, m.p. >250 °C; δ_C 135.55 (COP) and 138.33 (CCl); δ_P −3.86 (Found: C, 15.1; H, 1.5; P, 19.5. $C_6H_6Cl_3O_{12}P_3$ requires C, 15.33; H, 1.21; P, 19.80%).

Cyanoketene **1d**. The ketene was isolated from the reaction

mixture by liquid nitrogen trapping from the reaction of the cyano ester **2e** with phosphoric anhydride. Cyanoketene condensed as a colourless liquid, b.p. −34 °C. It was stored as a refrigerated solution in carbon tetrachloride; δ_H 5.28; δ_C 52.2 (C–CN), 118.4 (CN) and 208.7 (C=O).

2,4,6-Tricyanocyclohexane-1,3,5-trione **4**. The solid residue of the reaction of ester **2e** and phosphoric anhydride as described above was extracted with tetrachloromethane and produced a solution of the compound **4**. Evaporation gave orange crystals of the mixture of compounds **4** and **3b** with the cyclohexane-trione **4** dominating, m.p. 64–66 °C; $\delta_H(CCl_4)$ 7.25; δ_C 97.68 (C–CN), 116.46 (CN) and 157.07 (C=O); m/z 201 (M$^+$) (Found: C, 53.7; H, 1.4; N, 20.7. $C_9H_3N_3O_3$ requires C, 53.73; H, 1.49; N, 20.89%).

2,4,6-Tricyanobenzene-1,3,5-triol **3b**. The residue from the previous extraction was re-extracted with tetrachloromethane–trichloromethane (50:50 v/v). Evaporation of the solvent mixture produced red crystals of a mixture of **4** and **3b** with the latter compound dominating, m.p. 53–55 °C; $\delta_H([^2H_6]acetone)$ 4.82; δ_C 116.94 (CN), 127.32 (C–CN) and 142.91 (COH); m/z 201 (M$^+$) (Found: C, 53.6; H, 1.5; N, 20.7. $C_9H_3N_3O_3$ requires C, 53.73; H, 1.49; N, 20.89%).

Cyanoacetic dihydrogen phosphoric anhydride **6a**. The residue from the previous extraction was re-extracted with acetone. Fractional crystallisation from acetone gave a brown solid which was recrystallized from dioxane, m.p. 105 °C; δ_H 3.40 (CH$_2$) and 5.56 (OH); δ_C 28.92 (CH$_2$), 116.06 (CN) and 189.15 (C=O); δ_P −3.46 (Found: C, 21.4; H, 22.2; N, 8.7; P, 18.4. $C_3H_4NO_5P$ requires C, 21.81; H, 2.42; N, 8.48; P, 18.79%).

Cyanoacetic trihydrogen pyrophosphoric anhydride **6b**. The residue from the previous extraction was re-extracted with acetone–ethyl acetate (70:30 v/v). Fractional crystallization from the solvent mixture gave a yellow solid, m.p. 169 °C; δ_H 3.12 (CH$_2$) and 5.75 (br, OH); δ_C 28.69 (CH$_2$), 115.97 (CN) and 188.72 (C=O); δ_P −8.46 and 1.29 (Found: C, 14.3; H, 2.4; N, 5.9; P, 25.0. $C_3H_5NO_8P_2$ requires C, 14.69; H, 2.04; N, 5.71; P, 25.30%).

Bis(2,4,6-tricyano-3,5-dihydroxyphenyl) hydrogen phosphate **3o**. The residue from the previous extraction was re-extracted with ethyl acetate. Evaporation of ethyl acetate gave an orange solid, m.p. 147 °C; δ_C 116.30 (CN), 123.11 (C–CN) and 129.84 (COP); δ_P −11.43 (Found: C, 46.3; H, 1.4; N, 17.9; P, 6.3. $C_{18}H_5N_6O_8P$ requires C, 46.55; H, 1.07; N, 18.10; P, 6.68%).

2,4,6-Tricyano-3,5-dihydroxyphenyl dihydrogen phosphate **3d**. The residue from the previous extraction was re-extracted with acetone–ethanol (30:70 v/v). Evaporation of the solvent mixture gave a magenta solid which was purified by trituration with hexane and tetrachloromethane, m.p. 78 °C; δ_C 117.25 (CN), 119.64 (C–CN), 131.13 (COP) and 146.20 (COH); δ_P −2.74 (Found: C, 38.2; H, 1.7; N, 14.8; P, 11.05. $C_9H_4N_3O_6P$ requires C, 38.43; H, 1.42; N, 14.94; P, 11.03%).

2,4,6-Tricyanobenzene-1,3,5-triyl tris(dihydrogen phosphate) **3l**. The residue from the previous extraction was re-extracted with ethanol. Evaporation of ethanol gave a yellow solid which was recrystallized from acetone–ethanol (75:25 v/v), m.p. 168 °C; δ_C 117.96 (CN), 122.80 (C–CN) and 134.02 (COP); δ_P 2.00 (Found: C, 24.2; H, 1.55; N, 9.2; P, 20.7. $C_9H_6N_3O_{12}P_3$ requires C, 24.48; H, 1.36; N, 9.52; P, 21.08%).

2,4,6-Tricyanobenzene-1,3,5-triyl tris(trihydrogen pyrophosphate) **3m**. The residue from the previous extraction was re-extracted with methanol. Evaporation of methanol gave a red solid which was recrystallized from acetone–ethyl acetate (80:20 v/v), m.p. 207 °C; δ_C 117.31 (CN), 124.16 (C–CN) and 131.76 (COP); δ_P −8.85 and 1.67 (Found: C, 15.3; H, 1.7; N, 6.0; P, 27.1. $C_9H_9N_3O_{21}P_6$ requires C, 15.86; H, 1.32; N, 6.16; P, 27.31%).

3,5-Dihydroxy-2,4,6-trinitrophenyl dihydrogen phosphate **3e**.

The solid residue from the reaction of ester **2g** and phosphoric anhydride as described above was extracted with acetone. Evaporation of acetone gave a black solid, m.p. 65–67 °C; δ_C 129.33 (COP), 140.33 (COH) and 144.71 (CNO$_2$); δ_P −4.12 (Found: C, 20.8; H, 1.45; N, 12.6; P, 8.8. C$_6$H$_4$N$_3$O$_{12}$P requires C, 21.11; H, 1.17; N, 12.81; P, 9.09%).

2,4,6-Trinitrobenzene-1,3,5-triyl tris(trihydrogen pyrophosphate) **3n**. The residue from the previous extraction was re-extracted with methanol–ethyl acetate (50:50 v/v). Fractional crystallization from the solvent mixture gave a dark violet solid which was purified by trituration with acetone, m.p. >250 °C; δ_C 126.42 (COP) and 143.55 (CNO$_2$); δ_P −4.30 and 2.02 (Found: C, 17.4; H, 1.2; N, 5.0; P, 24.7. C$_6$H$_9$N$_3$O$_{27}$P$_6$ requires C, 17.71; H, 1.11; N, 5.16; P, 25.10%).

Bis(2,4,6-tricarboxy-3,5-dihydroxyphenyl) hydrogen phosphate **3r**. The solid residue from the reaction of ester **2h** and phosphoric anhydride as described above was extracted with acetone–ethanol (40:60 v/v). Fractional crystallization from the solvent mixture gave a dark yellow solid, m.p. 65 °C; δ_C 127.93 (C-CO$_2$H), 131.67 (COP), 150.10 (COH) and 187.21 (CO$_2$H); δ_P −11.98 (Found: C, 37.1; H, 1.8; P, 5.2. C$_{18}$H$_{11}$O$_{20}$P requires C, 37.37; H, 1.90; P, 5.36%).

2,4,6-Tricarboxy-3,5-dihydroxyphenyl dihydrogen phosphate **3p**. The residue from the previous extraction was re-extracted with acetone–ethanol (10:90 v/v). Fractional crystallization from the solvent mixture gave a brown solid which was purified by trituration with acetone, m.p. >250 °C; δ_C 128.88 (C-CO$_2$H), 132.41 (COP), 143.02 (COH) and 191.20 (CO$_2$H); δ_P −2.73 (Found: C, 31.8; H, 2.0; P, 9.7. C$_9$H$_7$O$_{12}$P requires C, 31.95; H, 2.08; P, 9.17%).

2,4,6-Tricarboxybenzene-1,3,5-triyl tris(dihydrogen phosphate) **3q**. The residue from the previous extraction was re-extracted with ethanol–methanol (50:50 v/v). Evaporation of the solvent mixture gave a brown–red solid which was purified by trituration with acetone–ethanol (75:25 v/v), m.p. >250 °C; δ_C 129.60 (C-CO$_2$H), 133.18 (COP) and 190.68 (CO$_2$H); δ_P −2.84 (Found: C, 21.5; H, 1.9; P, 18.9. C$_9$H$_9$O$_{18}$P$_3$ requires C, 21.68; H, 1.80; P, 18.67%).

References

1 Part 2, D. A. Efremov, J. C. Tebby and P. M. Zaulin, *Phosphorus, Sulfur, Silicon Relat. Elem.*, in the press.
2 P. Bamfield and P. F. Gordon, *Chem. Soc. Rev.*, 1984, **13**, 441.

3 H. Leuchs and A. Geseric, *Chem. Ber.*, 1908, **41**, 4171.
4 A. Combes, *Bull. Soc. Chim.*, 1894, **11**, 710.
5 R. N. Lacey, *Ketenes in The Chemistry of Alkenes*, Interscience Publishers, London, New York, 1964, p. 1161.
6 J. L. E. Erickson and G. C. Kitchens, *J. Org. Chem.*, 1962, **27**, 460.
7 R. H. Hasek, R. D. Clark, E. U. Elam and R. G. Nations, *J. Org. Chem.*, 1962, **27**, 3106.
8 O. Diels and Y. Wolf, *Ber.*, 1906, **39**, 689.
9 O. Diels and G. Meyerheim, *Ber.*, 1907, **40**, 82.
10 A. Stock and H. Stolrenberg, *Ber.*, 1917, **50**, 498.
11 T. Kappe and E. Ziegler, *Angew. Chem., Int. Ed. Engl.*, 1974, **13**, 491.
12 K. R. Roberts and C. G. De Puy, *Zh. Obshch. Khim.*, 1989, **59**, 2153.
13 D. A. Dorsey, S. M. King and H. W. Moore, *J. Org. Chem.*, 1986, **51**, 2814.
14 P. L. Fishbein and H. W. Moore, *J. Org. Chem.*, 1984, **49**, 2190.
15 D. M. Kunert, R. Chambers, F. Mercer, L. Hernandez and H. W. Moore, *Tetrahedron Lett.*, 1978, 929.
16 B. Rozsondai, J. Tremmel, I. Hergittai, V. N. Khabashesku, N. D. Kagramanov and O. M. Nefedov, *J. Am. Chem. Soc.*, 1989, **111**, 2845.
17 V. N. Khabashesku, A. K. Maltsev and O. M. Nefedov, *Dokl. Akad. Sc. USSR*, 1987, **296**, 403.
18 A. F. Eleev, I. L. Knuniants, S. I. Pletniov and G. A. Sokolski, *U.S.S.R.* N 598,885, 1978.
19 H. R. Seikaly and T. T. Tidwell, *Tetrahedron*, 1986, **42**, 2587.
20 M. T. Nguyen and A. F. Hegarty, *J. Am. Chem. Soc.*, 1984, **106**, 1552.
21 P. M. Zavlin and D. A. Efremov, *Zh. Obshch. Khim.*, 1988, **58**, 2403.
22 P. M. Zavlin and D. A. Efremov, *Phosphorus Sulfur*, 1990, **49/50**, 247.
23 V. V. Perekalin, E. S. Lipina, V. M. Berestovitskaya and D. A. Efremov, *Nitroalkenes*, John Wiley and Sons, 1994, p. 26.
24 L. R. Snyder and J. J. Kirkland, *Introduction to Modern Liquid Chromatography*, John Wiley and Sons, 1974, p. 255.
25 B. E. Ivanov, V. F. Zheltuhin and V. N. Eliseenkov, in *Chemistry and Application of Organophosphorus Compounds*, 8 Vsesouzn. Conf. (USSR), Nauka: Moscow, 1987, p. 258.
26 S. D. Morely, R. J. Abraham, D. E. Jackson, M. R. Saunders and J. G. Vinter, *J. Comput. Aided Mol. Design*, 1991, **5**, 475.
27 R. J. Abraham and P. E. Smith, *J. Comput. Chem.*, 1988, **9**, 288.
28 P. M. Zavlin, D. A. Efremov and N. S. Essentseva, *Zh. Obshch. Khim.*, 1991, **61**, 1269.