inert solvent and the addition was conducted at low temperatures (usually −78°). This procedure has been successful for conjugated olefins such as indene,[1] acenaphthylene,[1] stilbene, and substituted phenanthrenes,[2] as well as for α,β-unsaturated acid halides.[2] *cis* addition was the predominant process with stilbene, acenaphthylene, and the phenanthrenes.[1,2] The only other alternate procedures utilize PbF_4[3] and perhaps $C_6H_5IF_2$[4] and are neither as general nor as simple as one would prefer.

Direct fluorination of Δ^4-cholesten-3-one proceeds smoothly in CCl_3F at −78° to produce the *cis*-4,5-difluoride in yields of 60–70%. The crude adduct mixture was purified from unreacted cholestenone by silica gel chromatography followed by crystallization from methanol and affords the adduct as colorless crystals, mp 187–188°. *Anal.* Calcd for $C_{27}H_{44}F_2O$: C, 76.73; H, 10.49; F, 8.99. Found: C, 76.54; H, 10.76; F, 9.40.

The infrared spectrum of the difluoride contained a carbonyl absorption at 5.72 μ indicative[5] of an α-fluorine substituent. The usual C–F absorption was noted between 8.7 and 9.6 μ. Dehydrofluorination of the adduct (sodium methoxide in methanol) gave 4-fluoro-4-cholesten-3-one, mp 102–103°.[6]

The F^{19} nmr spectrum contained two multiplets centered at ϕ +170.1 and 207.4[7] in an integrated ratio of 1:1. The low-field (ϕ 170.1) multiplet was too complex to interpret and assigned the fluorine atom at C-5. The higher field group (α to the carbonyl) was a pair of doublets with couplings of 47 and 12 cps. The 47 cps coupling is indicative[8] of a geminal J_{HF} and the minor (12 cps) value is assigned as J_{FF}.

The proton nmr spectrum contains two doublets centered at δ 5.0 which are assigned the single C_4 proton geminal to a fluorine atom. The geminal J_{HF} of 47.0 cps is readily apparent. The J_{HF} vicinal then remains with a value of 32.6 cps. This large J_{HF} is sufficient to assign the stereochemistry of the adduct as *cis*.[9] It has been shown[9] that J_{HF} (axial–axial) = 23.4–25.4 cps and J_{HF} (equatorial–axial) = 4.9–11.7 cps in the glycopyranosyl fluorides. *trans*-Diaxial orientation of C_4-hydrogen and C_5-fluorine atoms demands *cis* orientation of fluorine atoms.

The isolated double bond of cholesteryl chloride could also be smoothly fluorinated to the 5,6-difluoride, mp 103–104°. *Anal.* Calcd for $C_{27}H_{45}ClF_2$: C, 73.19; H, 10.24; F, 8.58. Found: C, 73.17; H, 10.55; F, 8.41). The F^{19} nmr spectrum contained a broad band at ϕ +179.7 assigned to the fluorine atom at C_5 and a complex doublet ($J \approx 40$ cps) at ϕ 194.5. The 40 cps value is suggestive of geminal HF coupling[7] and is assigned as the fluorine atom at C_6. The spectrum is too complex to assign this fluorine atom to position 4 where there is only one vicinal proton. The vicinal HF coupling constants could not be obtained since the appropriate region was obscured by the absorption of the proton geminal to the chlorine atom. The stereochemistry is assigned *cis* by analogy with the cholestenone case and the other examples.[1,2,10]

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(3) A. Bowers, P. G. Holton, E. Denot, M. C. Loza, and R. Urquiza, *J. Am. Chem. Soc.*, **84**, 1050 (1962).
(4) P. G. Holton, A. D. Cross, and A. Bowers, *Steroids*, **2**, 71 (1963).
(5) L. J. Bellamy, "The Infrared Spectra of Complex Molecules," John Wiley and Sons, Inc., New York, N. Y., 1957.
(6) S. Nakanishi, R. L. Morgan, and E. V. Jensen, *Chem. Ind.* (London), 1137 (1960), report mp 100–101°, $\gamma_{C=O}$ 1688 cm^{-1} for this steroid. Our sample had $\gamma_{C=O}$ Nujol at 1686 cm^{-1} and an F^{19} nmr peak at ϕ +140.2.
(7) F^{19} nmr data are given in values of ϕ (ppm from CCl_3F as internal standard).
(8) J. A. Pople, *Mol. Phys.*, **1**, 216 (1958).
(9) L. D. Hall and J. F. Manville, *Chem. Ind.* (London), 991 (1965).
(10) The *cis* addition to cholesteryl chloride also is supported by the following observations. Fluorination of cholesteryl acetate gives a low yield (10–20%) of 5α,6α-difluorocholestan-3β-ol acetate, mp 117–118°,[11] F^{19} nmr peaks at ϕ +178.9 and +194 (doublet, geminal $J_{HF} \cong 46$ cps). This acetate was converted by the method of Barnes and Djerassi[11] to 5α,6α-difluorocholestan-3-one, mp 171–172°,[11] F^{19} nmr peaks at ϕ +174.9 and +196 (doublet, geminal $J_{HF} \cong 46$ cps). Direct fluorination of Δ^6-cholesten-3-one has not proceeded satisfactorily.
(11) C. S. Barnes and C. Djerassi, *J. Am. Chem. Soc.*, **84**, 1962 (1962), report mp 120–121° for the 5α,6α-difluorocholesteryl acetate and mp 173–174° for 5α,6α-difluorocholestan-3-one.

Richard F. Merritt, Travis E. Stevens
Rohm and Haas Company, Redstone Research Laboratories
Huntsville, Alabama
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2,4-Dinitrophenyl Phosphate

Sir:

The synthesis of 2,4-dinitrophenyl phosphate has eluded the best efforts of a series of investigators.[1] This has led some of them to suppose that the ester must be exceptionally labile, a point of some interest in connection with its possible role in the uncoupling action of dinitrophenol in oxidative phosphorylation.[2]

We have prepared 2,4-dinitrophenyl phosphate in near-quantitative yield by the debenzylation of the dibenzyl ester. This is readily prepared from the phenol and dibenzyl phosphorochloridate in dry ether, in the presence of 1 mole of 2,6-lutidine. After refluxing for 1.5 hr the solution is filtered hot to remove 2,6-lutidine hydrochloride, and the ester crystallizes on cooling. Recrystallization from ether gives colorless crystals, mp 65–66°.

Two grams of the triester is suspended in 50 ml of dry ether and dry HBr passed slowly into the solution at room temperature. After 1.5 hr HBr is no longer absorbed, and a yellow oil has separated. After removal of the solvent, and traces of HBr, *in vacuo*, the residue is dissolved in a large volume of dry ether and 2,6-lutidine added until the solution just turns yellow (1.1–1.2 g). A voluminous white precipitate of the mono-2,6-lutidinium salt is formed. After filtration, and recrystallization from ethanol, this has mp 142° dec. The yield is about 90%. *Anal.* Calcd. for $C_{13}H_{14}N_3O_8P$: C, 42.1; H, 3.77; N, 11.32; P, 8.35. Found: C, 41.7; H, 4.00; N, 11.49; P, 8.29.

One of us has shown previously[3] that a plot of the logarithms of the rate constants for hydrolysis of sub-

(1) (a) M. Rapp, *Ann. Chem.*, **224**, 156 (1884); (b) V. H. Parker, *Biochem. J.*, **69**, 306 (1958); (c) R. Wittmann, *Chem. Ber.*, **96**, 771 (1963); (d) R. Azerad, D. Gautheron, and M. Vilkas, *Bull. Soc. Chim. France*, 2078 (1963).
(2) (a) W. F. Loomis and F. Lipmann, *J. Biol. Chem.*, **201**, 357 (1953); (b) F. Hunter in "Phosphorus Metabolism," Vol. 1, W. D. McElroy and B. Glass, Ed., Johns Hopkins Press, Baltimore, Md., 1951, p 297.
(3) A. J. Kirby and W. P. Jencks, *J. Am. Chem. Soc.*, **87**, 3209 (1965).

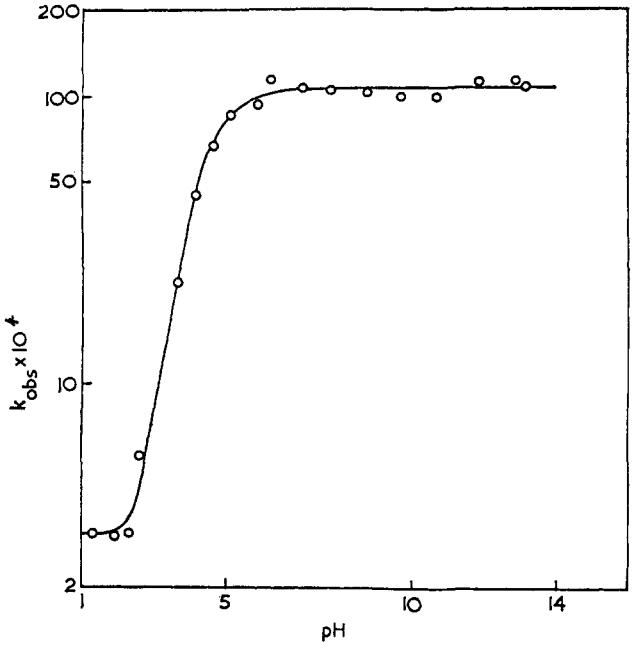
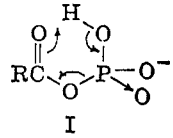


Figure 1. pH–rate profile for the hydrolysis of 2,4-dinitrophenyl phosphate in aqueous solution of ionic strength 1.0, at 39°.

stituted benzoyl phosphate dianions[4] *vs.* the pK_a of the leaving group gives a straight line on which the value for the dianion of *p*-nitrophenyl phosphate also falls. The dianion of 2,4-dinitrophenyl phosphate is hydrolyzed just twice as fast as predicted from this plot, with a half-life of 66 min at 39° and ionic strength 1.0.

The monoanion is hydrolyzed at less than $^1/_{30}$ this rate (Figure 1). This reversal of the usual relative reactivities of mono- and dianion has been observed with certain acyl phosphates,[4,5] but not previously with a phosphate ester. It is a consequence of the much greater sensitivity of the rate of hydrolysis of the dianionic species to the pK_a of the leaving group.[6]

The ratio of the hydrolysis rates of dianion and monoanion is some 20 times larger than that observed for benzoyl phosphates with leaving groups with pK_a comparable to that of 2,4-dinitrophenol. This factor may be a measure of the efficiency of the special mechanism available to the monoanions of acyl phosphates suggested by Jencks;[4] this mechanism involves intramolecular protonation of the leaving group in a six-membered cyclic transition state, I.



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(4) G. Di Sabato and W. P. Jencks, *J. Am. Chem. Soc.*, **83**, 4400 (1961).
(5) A. Marcus and W. B. Elliott, *ibid.*, **80**, 4287 (1958).
(6) The plot of log k_{hyd} against pK_a of the leaving group for the dianions of acyl and monoaryl phosphates has a slope of 1.2 at 39°. The slope of the corresponding plot for the monoanions of a wide range of monoalkyl and monoaryl phosphates at 100° is 0.27.[7]
(7) A. J. Kirby and A. G. Varvoglis, to be published.

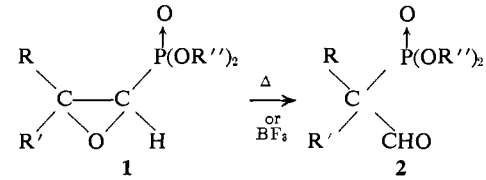
A. J. Kirby, A. G. Varvoglis
University Chemical Laboratory
Cambridge, England

Received February 21, 1966

1,2 Shifts of Dialkoxyphosphono Groups in Skeletal Rearrangements of α,β-Epoxyvinylphosphonates[1]

Sir:

A variety of rearrangements of organophosphorus compounds involving migration of a phosphorus substituent from carbon to oxygen,[2a] oxygen to carbon,[2b] nitrogen to oxygen,[2c] and oxygen to oxygen[2d] have been characterized. However, no comparable shifts from carbon to carbon paralleling the well-known skeletal rearrangements of organic compounds have been reported. We have observed what we believe to be the first example of such a rearrangement, namely, the thermal and acid-catalyzed rearrangement of α,β-epoxyvinylphosphonates (**1**) to α-formylalkylphosphonates (**2**).



1 **2**

a, R = C_6H_5; R′ = CH_3; R″ = C_2H_5
b, R = R′ = CH_3; R″ = CH_3
c, R = R′ = C_6H_5; R″ = C_2H_5
d, R = R′ = C_6H_5; R″ = CH_3
e, R = R′ = $-(CH_2)_5-$; R″ = C_2H_5
f, R = C_6H_5; R′ = H; R″ = C_2H_5

Distillation of diethyl α,β-epoxy-β-methyl-β-phenylvinylphosphonate[3] [**1a**, bp 97–100° (0.05 mm)] at 170° (0.7 mm) led to the isolation of the product of diethoxyphosphono group migration, diethyl α-formyl-α-phenylethylphosphonate [**2a**, bp 131–133° (0.7 mm), ν_{CO} 1724 cm^{-1}],[4] in 86% yield.[5] Trace amounts of atropaldehyde (**3**) and diethyl phosphite (**4**) were also isolated. It was shown in a separate experiment that **3** and **4** represent thermal decomposition products of **2a** and not primary products from **1a**. Analogous rearrangements were observed for the epoxides **1b–1d** at 200–300° (0.6–0.7 mm). The rearranged products (**2e**, **2f**) of epoxides **1e** and **1f** are apparently unstable at the temperatures (270–300°) required for rearrangement and only the dephosphonated aldehydes are isolated, *e.g.*, cyclohexene-1-carboxaldehyde and **4** are formed from **1e**. However, rearrangement of **1e**

(1) Phosphonic Acids and Esters. XIV. Part XIII: M. Gordon and C. E. Griffin, *J. Org. Chem.*, **31**, 333 (1966).
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(3) The epoxides (**1**) were prepared in acceptable yield by the Darzens condensation of the dialkyl chloromethylphosphonate with the appropriate aldehyde or ketone; sodium hydride in dimethyl sulfoxide proved to be the most effective condensation agent. The only previous report of the preparation of an epoxyphosphonate by the Darzens route is that of V. F. Martynov and V. E. Timofeev [*J. Gen. Chem. USSR*, **32**, 3383 (1962)]; these workers obtained **1e** by condensation with cyclohexanone in the presence of sodium ethoxide.
(4) The product of hydrogen migration, $C_6H_5(CH_3)CHCOP(O)(OC_2H_5)_2$, would be expected to show ν_{CO} of a lower frequency, *e.g.*, $CH_3COP(O)(OC_2H_5)_2$, ν_{CO} 1695 cm^{-1}.
(5) The infrared and pmr spectra and elemental analyses of **1** and **2** were in complete accord with the postulated structures. The unsaturated aldehydes (*e.g.*, **3**) were characterized as their 2,4-dinitrophenylhydrazones.