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Aliphatic organophosphorus nitro-compounds

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ABSTRACT. The review presents data on the methods of synthesis and properties of aliphatic organophosphorus α-, β-, γ-, and δ-nitro-compounds. They are arranged in conformity with the structural types of the compounds, since there are no general methods of synthesis characteristic simultaneously of all the groups of organophosphorus nitro-compounds.

The bibliography includes 109 references.

Contents

I. Introduction 1220
II. Organophosphorus α-nitro-compounds 1220
III. Organophosphorus β-nitro-compounds 1224
IV. Organophosphorus γ-nitro-compounds 1231
V. Organophosphorus δ-nitro-compounds 1233
VI. Conclusion 1234

I. Introduction

The interest in the study of aliphatic organophosphorus nitro-compounds is due primarily to the wide variety of their reactions involving the electron-accepting groups (the nitro-group and the phosphoryl group) linked to alkyl and alkenyl residues, which is the reason for the great importance of such compounds in synthetic and theoretical organic chemistry.

The synthesis of aminoalkylphosphonic acids with functional group substituents via the nitro-derivatives opens the way to certain compounds which are otherwise difficult to obtain. Thus organophosphorus nitro-compounds can become important intermediates in the synthesis of pharmaceuticals, fungicides, herbicides, antibiotics, glutamate-ergic neuron blocking agents, etc.

In discussing the data, the aim was to trace (in so far as this was permitted by the published results) the dependence of the mode of the reactions on their experimental conditions and on the structure of the reactants, to demonstrate the relation between the physicochemical properties and structure of organophosphorus nitro-compounds, and also to describe their possible subsequent reactions.

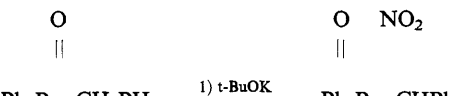
Certain reactions, discovered as a result of the search for ways of synthesising organophosphorus nitro-compounds, are of fundamental importance in organic synthesis.

II. Organophosphorus α-nitro-compounds

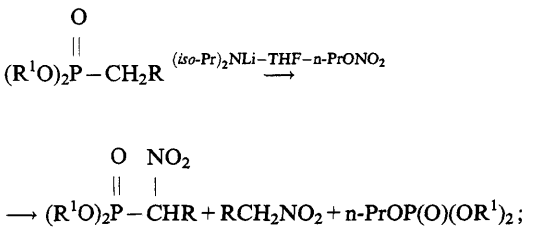
1. Methods of synthesis of organophosphorus α-nitro-compounds

The use of the most reactive trivalent phosphorus compounds for the synthesis of organophosphorus nitro-derivatives was hindered by the occurrence of numerous oxidation-reduction processes involving phosphorus(III).[1–3]

The first representative of organophosphorus α-nitro-compounds was obtained by nitrating with ethyl nitrate potassium benzyldiphenylphosphine oxide metallated with the aid of potassium t-butoxide:[4]



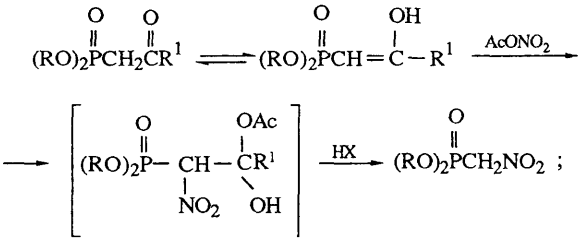
Nitration of alkylphosphonates with alkyl nitrates in the lithium isopropylamide–tetrahydrofuran (THF) system leads to cleavage products (nitroalkanes and trialkyl phosphates) together with nitrophosphonates:[5]



R = Bu, C_5H_{11}.

The attempt to suppress the cleavage of the initial ester by using bulky substituents at the phosphorus atom (for example, isopropoxy-groups) failed and the yield of the nitroalkylphosphonates is also low in this case.

The interaction of phosphorylated aldehydes and ketones with acetyl nitrate in acetic anhydride at 30–35 °C also leads to nitromethylphosphonates.[6,7] It has been suggested[8] that the reaction proceeds via an enol formation stage in accordance with the mechanism

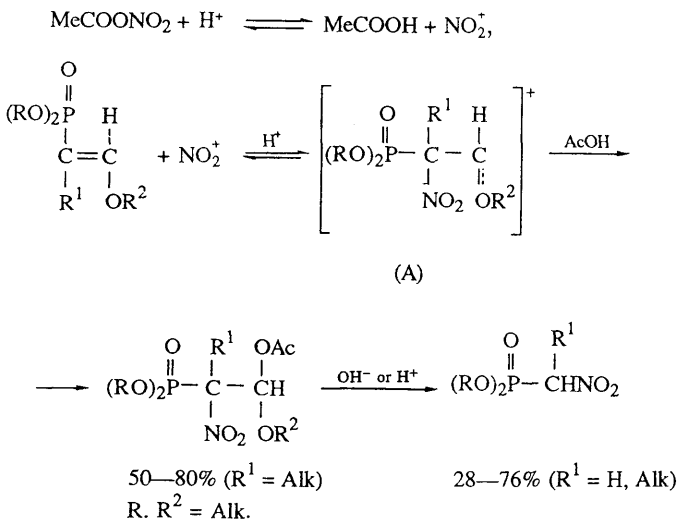


R = Alk; R^1 = H, Me; $X = OH^-, AcO^-$.

The introduction of electronegative substituents into the methylene group in β-ketophosphonates prevents this reaction. Thus diethyl

1-chloro-2-oxoalkylphosphonate does not react with acetyl nitrate at 33–35 °C, while at a higher temperature it decomposes under the reaction conditions.

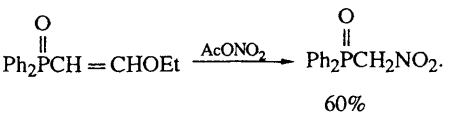
A more convenient method of synthesis of 1-nitroalkylphosphonates involves the interaction of 2-alkoxyvinylphosphonate with acetyl nitrate. The final products can be readily separated from the initial reactants by converting them into the aci-form with subsequent acidification.[6,9] The reaction is catalysed by sulphuric acid (apparently as a consequence of the enhancement of the electrophilicity of the reagent $MeCOONO_2.H^+$).[7] The addition of acetyl nitrate is not stereospecific—diastereoisomers are formed in proportions of 45:55. The reaction apparently proceeds via a stage involving the addition of the nitronium cation to the vinylphosphonate with subsequent nucleophilic attack on the relatively stable planar carbonium ion (A) by acetic acid or the acetate ion, the attack being directed with equal probability "from the front and from the rear".



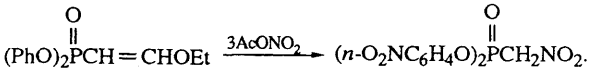
In the presence of an alkyl group in the α-position relative to the phosphonate group, the adduct is stable and on treatment with bases (sodium alkoxide, alcoholic alkali) or hydrochloric acid gives rise to 1-nitroalkylphosphonate.[10]

The stability of the adducts formed by the addition of acetyl nitrate to 2-alkoxy-1-alkylvinylphosphonates can be accounted for by the presence of the alkyl group, which causes steric hindrance to the conjugation between the C–C bond and the π-system of the nitro-group. The stability of the carbonium ion (A) is also affected by the 2-alkoxy-group, which hinders the nucleophilic attack: in its absence (diethyl 1-ethyl-2-oxoethylphosphonate), the ion (A) is cleaved in the instant of reaction. Thus slight changes in the structure of phosphonates affect the course of the reaction with acetyl nitrate and the structure of the products. For example, nitration products cannot be obtained from diethyl 2-ethoxy-2-methylvinylphosphonate.

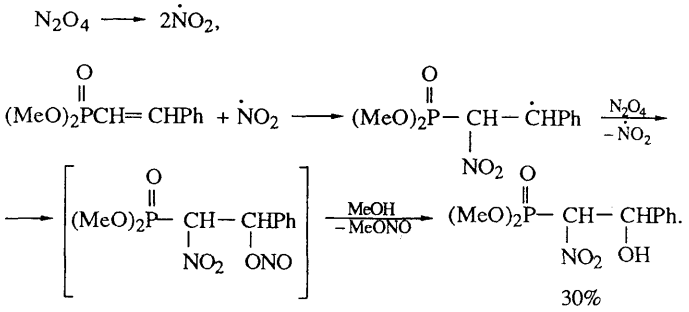
Nitration with acetyl nitrate of the corresponding 2-alkoxyalkenylphosphinates and 2-alkoxyalkenylphosphine oxides also leads to nitromethylphosphinates and nitromethylphosphine oxides.[11] The authors explain a certian passivity of phosphine oxides in the reaction by the competing protonation of the phosphoryl group, and not acetyl nitrate, by sulphuric acid, which lowers the activity of the catalyst. Only nitromethyldiphenylphosphine oxide, in which the phosphoryl group is less basic, is obtained in a high yield.



In the case of diphenyl esters of 2-ethoxyvinylphosphonic acid, acetyl nitrate nitrates simultaneously both the double bond and the benzene ring:[11]

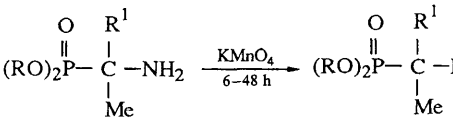


Nitration of 2-phenylvinylphosphonate with dinitrogen tetroxide leads to an organophosphorus α-nitroalcohol.[12] The reaction is accompanied by the cleavage of the C–P and C–C bonds, which was confirmed by the isolation of 2-nitrostyrene and 2-nitrophenol from the reaction mixture.



According to IR spectroscopic data, organophosphorus α-nitroalcohols form intermolecular hydrogen bonds in the crystal [ν(OH) = 3280 cm^{-1}], which are readily ruptured on dissolution with formation of free molecules [ν(OH) = 3590 cm^{-1}]. The chemical shift of the hydroxyl proton (δ_{OH} = 2.93 p.p.m.) in the ^1H NMR spectra also corresponds to the virtually free state of the OH group.

1-Aminoalkylphosphoantes substituted in the 1-position are oxidised by potassium permanganate or hydrogen peroxide to the corresponding α-nitroalkyl phosphonates:[6,13]



1-Nitroalkylphosphonates have also been obtained by oxidising with *m*-chloroperbenzoic acid 1-*N*-hydroxyiminoalkylphosphonates synthesised beforehand from 1-oxoalkylphosphonates, which were

obtained in their turn by the reaction of acyl chlorides with triisopropyl phosphite.[14]

$$(\text{iso-PrO})_3\text{P} \xrightarrow{\text{RCOCl}} (\text{iso-PrO})_2\text{P}(\text{O})\text{C}(\text{O})\text{R} \xrightarrow[\text{2) m-ClC}_6\text{H}_4\text{COOOH/CH}_2\text{Cl}_2]{\text{1) NH}_2\text{OH·HCl/C}_5\text{H}_5\text{N}} (\text{iso-PrO})_2\text{P}(\text{O})\text{CH}(\text{NO}_2)\text{R};$$

50–65%

R = Me, Et, $PhCH_2$.

Only one instance of the synthesis of an organophosphorus(III) α-nitro-compound from the sodium salt of 1-nitropropane and diethyl phosphorochloridite has been described in the literature.[1]

$$(\text{CH}_3\text{CH}_2\text{CH}{=}\text{NO}_2)^-\text{Na}^+ + (\text{EtO})\text{P}{-}\text{Cl} \rightarrow (\text{EtO})_2\text{P}(\text{O})\text{CH}(\text{NO}_2)\text{CH}_2\text{CH}_3.$$

13%

The phosphorylation with dialkyl phosphorochloridate of the dilithium salts of nitroalkanes obtained by the reaction of lithium diisopropylamide (LDA) with nitroalkanes at –78 °C takes place more sucessfully.[15] In order to diminish the occurrence of the Neff side reaction, the reaction product is protonated with glacial acetic acid to give a nitroalkylphosphonate.

$$\text{RCH}_2\text{NO}_2 \xrightarrow[\text{2) (EtO)}_2\text{POCl/THF}]{\text{1) 2LDA/THF, –78 °C}} \left[(\text{EtO})_2\text{P}(\text{O})\text{CR}(\text{NO}_2)\right] \xrightarrow[\text{THF, –78 °C}]{\text{AcOH}} (\text{EtO})_2\text{P}(\text{O})\text{CHR}(\text{NO}_2);$$

47–75%

R = Me. Et.

The dialkylphosphite anion phosphorylates 2-chloro- or 2-(toluene-*p*-sulphonyl)-2-nitropropane in a free-radical $S_{RN}1$ reaction via the radical-ion of dialkyl phosphite with formation of α-nitroalkyl phosphonates.[16]

$$\text{O}_2\text{NCR}_2\text{X} + (\text{R}^1\text{O})_2\text{PO}^-\text{K}^+ \xrightarrow[45–25\ ^\circ\text{C}]{\text{THF}} (\text{R}^1\text{O})_2\text{P}(\text{O})\text{CR}_2\text{NO}_2;$$

X = Cl. *p*-$MeC_6H_4SO_2$; R = Me. $(CH_2)_4$; R^1 = Me. Et.

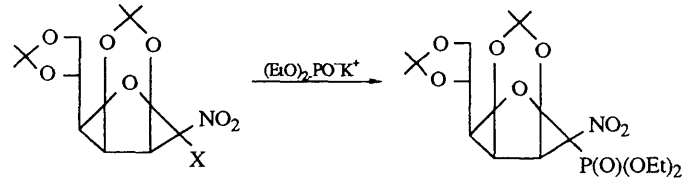
The reaction of 2,2-dinitropropane and 2-(toluene-*p*-sulphonyl)-2-nitropropane with the dialkyl phosphorothioite anion in dimethyl sulphoxide under irradiation takes place similarly.[17]

$$\text{Me}_2\text{C}(\text{X})\text{NO}_2 + (\text{RO})_2\text{PS}^-\text{K}^+ \xrightarrow[h\nu,\ 3.5\ \text{h}]{\text{M}_2\text{SO}} (\text{RO})_2\text{P}(\text{S})\text{CMe}_2\text{NO}_2 + \text{X}^-$$

30%

R = Me, X = NO_2; R = Et, X = *p*-$MeC_6H_4SO_2$.

The methods of synthesis of α-nitroalkylphosphonates have been used in carbohydrate chemistry to obtain phosphorus-containing derivatives.[18] Thus (1-*C*-nitroglycosyl)phosphonate was obtained from X-nitromannofuranose and potassium diethyl phosphite.



21—67%

X = Cl, *p*-$MeC_6H_4SO_2$.

The structure of organophosphorus α-nitro-compounds has been investigated by IR and NMR spectroscopy, which made it possible to discover the specific mutual influence of the nitro- and phosphoryl groups.

The ^{31}P chemical shift for α-nitroalkyl phosphonates (δ_P = 11–12 p.p.m.) is significantly lower than for other (β, γ, δ)-nitroalkylphosphonates. This can be explained by the strongly electron-accepting influence of the nitro-group.[12]

The characteristic absorption bands in the IR spectra of α-nitroalkyl phosphonates[5,6] at 1550–1560 [$\nu_{asym}(NO_2)$] and 1330–1360 [$\nu_{sym}(NO_2)$], 1260–1270 (P=O), 1120 and 1165 (POC), and 710 cm^{-1} (P–C bond) hardly differ from those for nitroalkanes and alkylphosphonates.

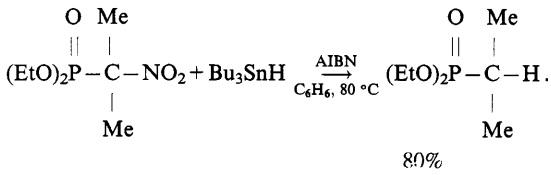
2. The chemical properties of organophosphorus α-nitro-compounds

The chemical properties of organophosphorus α-nitro-compounds are determined by their functional groups — the nitro-group and the phosphonate group. It is therefore useful to examine initially the chemical reactions associated with the nitro-group and then with the phosphonate group and finally other reactions specific to organophosphorus α-nitro-compounds.

Organophosphorus dialkyl nitro-compounds can be titrated potentiometrically in an aqueous medium with alkalis as weak monobasic acids.[6,7] Their ability to form sodium salts permits their purification via nitronic acids.[7,15]

The high CH acidity of organophosphorus α-nitroalkyl compounds is the cause of their reduced capacity for nucleophilic reactions. Thus they add with difficulty to derivatives of acrylic acid (the Michael reaction) and do not react with benzophenone.[19]

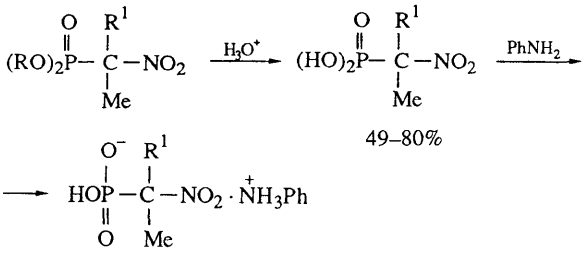
The nitro-group in tertiary organophosphorus α-nitro-compounds is readily substituted by hydrogen when the nitro-compound is treated with tributyltin hydride in the presence of azobisisobutyronitrile (AIBN).[20]



The interaction of diethyl (2,3 : 5,6-di-*O*-isopropylidene-1-nitro-α-D-mannofuranosyl)phosphonate with tributyltin hydride in the presence of AIBN leads to (2,3 : 5,6-di-*O*-isopropylidene-β-D-mannofuranosyl)phosphonate in 78% yield.[18]

Organophosphorus α-nitro-compounds are readily reduced catalytically in the presence of Raney nickel[4] and also with tin and hydrochloric acid[17] to the corresponding amino-derivatives.

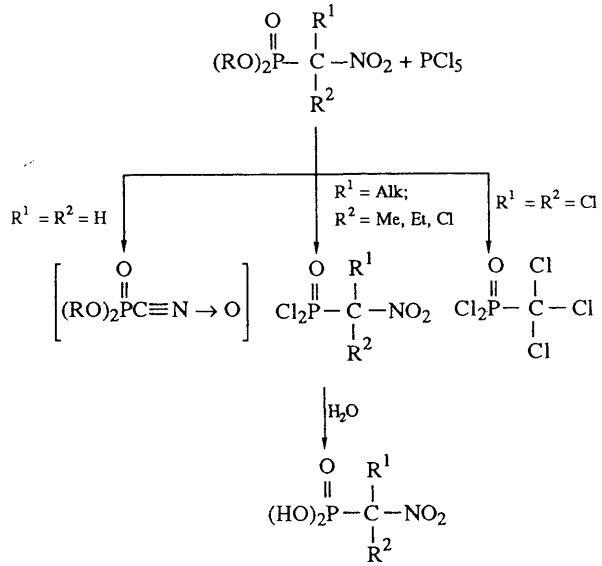
Acid hydrolysis of α-nitroalkylphosphonates not containing hydrogen atoms at the carbon atom linked to the nitro-group leads to high yields of the corresponding organophosphorus α-nitroacids, which were isolated in the form of monoanilinium salts.[6,13]



R, R^1 = Me, Et.

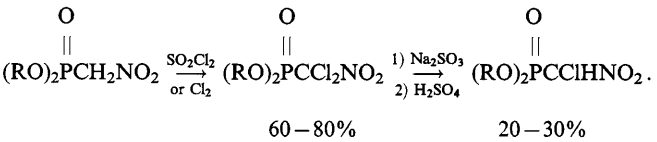
Hydrolysis of α-nitroalkylphosphonates containing hydrogen atoms at the α-carbon atom leads to their decomposition with formation of hydroxylamine hydrochloride (75%) and phosphoric acid.[7]

α-Nitroalkylphosphonates unsubstituted at the α-carbon atom, for example, diethyl nitromethylphosphonate, react with phosphorus pentachloride to form phosphonocyanidate *N*-oxide or its decomposition products, while the substituted derivative afford high yields of the hydrochlorides, which are then hydrolysed to the corresponding acids.[6,13] α-Nitroalkylphosphonates monochloro-substituted in the α-position,[21] for example, dimethyl 1-chloro-1-nitropropylphosphonate, react with phosphorus pentachloride to form the dichloride of 1-chloro-1-nitro-propylphosphonic acid in 72.5% yield. Its hydrolysis leads to the corresponding acid, which was isolated as the anilinium salt (64.8%). The interaction of dichloro-substituted diethyl nitromethylphosphonate with phosphorus pentachloride leads to the substitution not only of the alkoxy-group but also of the nitro-group by a chlorine atom, which results in the formation of the dichloride of trichloromethylphosphonic acid in 80% yield.



α-Nitroalkylphosphonates are readily brominated via the lithium salt to give the corresponding bromonitroalkylphosphonates.[5]

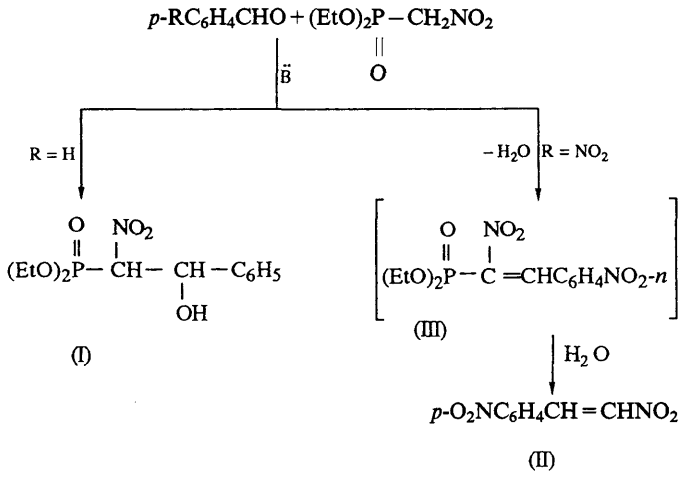
On treatment with sulphuryl chloride or chloride, the mobile hydrogen atoms in the methylene or methylidyne groups in α-nitroalkylphosphonates are substituted by a chlorine atom, which results in the formation of dichloronitroalkylphosphonates. These are readily converted into monochloro-derivatives on treatment with sodium sulphite.[21]



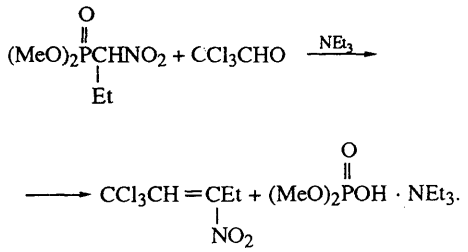
Chloronitromethylphosphonates behave in aqueous alcoholic solutions as weak monobasic acids. The IR spectra of these compounds are characterised by the presence of absorption bands at 1575 and 1350 cm^{-1} (NO_2), 1280 cm^{-1} (P=O), and 710 cm^{-1} (Cl). With increase in the number of chlorine atoms at the α-carbon atom, there is some increase in $\Delta\nu = \nu_{asym} - \nu_{sym}$ for the nitro-group: the corresponding frequencies ν_{asym} and ν_{sym} are 1560 and 1375 cm^{-1} for $(EtO)_2P(O)CH_2NO_2$, 1575 and 1350 cm^{-1} for $(EtO)_2P(O)CHClNO_2$, and 1600 and 1335 cm^{-1} for $(EtO)_2P(O)CCl_2NO_2$.

Diethyl nitromethylphosphonate reacts with benzaldehyde in the presence of piperidine to form diethyl 2-hydroxy-1-nitro-2-phenylethyl phosphonate (I) in 67% yield.[22] However, the reaction with *p*-nitrobenzaldehyde under the same or even milder conditions afforded 1-(*p*-nitrophenyl)-2-nitroethene (II) (80%). This course of the reaction is due to the presence of the electron-accepting nitro-group in the aromatic ring, which promotes the formation of the

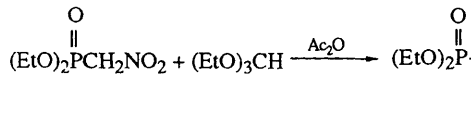
alkene (III), the latter being subsequently dephosphorylated to the more stable nitroalkene (II).



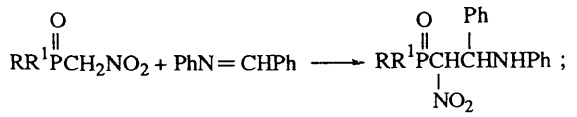
Similar elimination of the phosphonate group with formation of 1,1,1-trichloro-3-nitropent-2-ene is observed in the reaction of the highly electrophilic chloral with dimethyl 1-nitropropylphosphonate in the presence of triethylamine.[19]



Condensation of diethyl nitromethylphosphonate with triethyl orthoformate in acetic anhydride leads to diethyl 2-ethoxy-1-nitrovinylphosphonate in the form of a mixture of the (*E*)- and (*Z*)-isomers.[19]

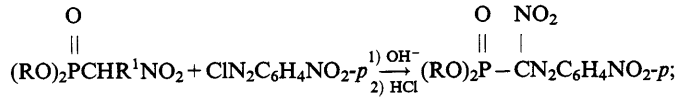


Organophosphorus α-nitro-compounds interact with benzylideneaniline in the absence of a catalyst.[19]



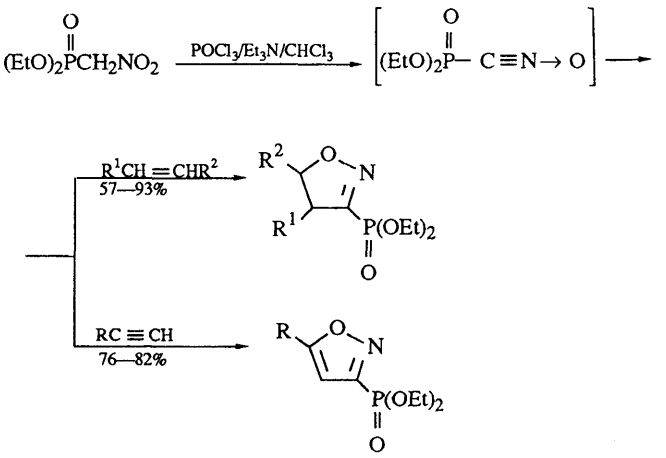
R, R^1 = OMe, OEt, Et, Ph.

α-Nitroalkylphosphonates enter into the azo-coupling reaction in an alkaline medium with *p*-nitrobenzenediazonium chloride.[19]



R = Me, Et; R^1 = H, Et.

On treatment with phosphoryl chloride in the presence of triethylamine, diethyl nitromethylphosphonate gives rise to a phosphorocyanidate *N*-oxide which at the instant of formation adds via the 1,3-dipolar cycloaddition mechanism to alkenes and alkynes with formation of the corresponding 3-diethoxyphosphoryl-4,5-dihydroizoxazoles and 3-diethoxyphosphorylisoxazoles.[23]

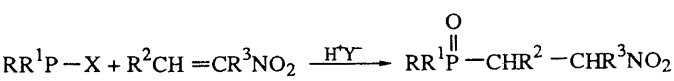


III. Organophosphorus β-nitro-compounds

1. Methods of synthesis of organophosphorus β-nitro-compounds

The study of the reactions of the full phosphites with nitroalkenes by a set of physicochemical methods demonstrated that the process proceeds via several competing pathways with formation of phosphoranes, alkenylphosphonates, β-nitroalkylphosphonates, oximes, nitriles, etc.[24]

The reactions of the full phosphites with nitroalkenes in proton-donating solvents lead mainly to organophosphorus β-nitro-compounds.[24–26]



R, R^1 = AlkO. PhO. Alk. Ph; R^2 = H. Alk. Ph;

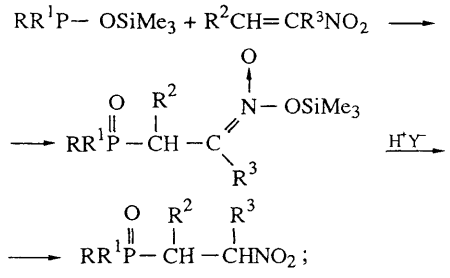
R^3 = H. Br. Et; X = AlkO; Y^- = OH^-. AcO^-.

The target products contain admixtures of α,β-unsaturated compounds. In order to reduce their content, appropriate protonating compounds and mixtures are selected: methanol,[27–29] phenol,[30] t-butyl alcohol–benzene,[31,32] water,[33,34] water–dioxane,[25,35,36] water–tetrahydrofuran,[37,38] water–dimethoxyethane,[39] acetic acid,[25] and *N*,*N*-diethylaniline hydrochloride in acetonitrile.[40]

The formation of the 1-nitroprop-1-ene radical-anion in the reaction of methyl diphenylphosphonite [methyl phenyl phenylphosphonite?] with 1-nitropropene was detected by the EPR method.[41,42] This reaction proved to be a convenient model for the determination of the thermodynamic parameters of the $P^{III} \leftrightarrows P^{V}$ equilibrium.[43]

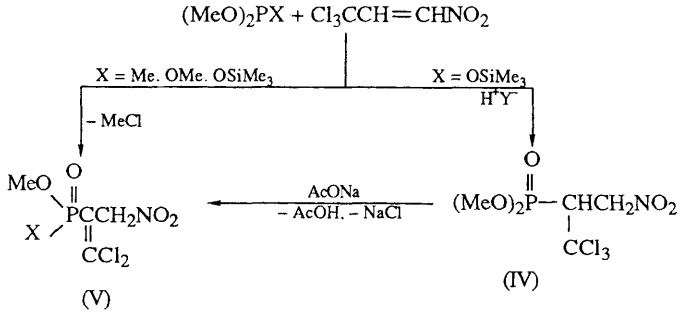
The reaction of silicon-containing derivatives of phosphorus(III) acids with nitroalkenes proved to be a more convenient method of synthesis of organophosphorus β-nitro-compounds. The first stage of this reaction involves the formation of the trimethylsilyl

esters of phosphorylated nitronic acids, which are then readily decomposed by water[34,44,45] and other proton-donating reagents (water-tetrahydrofuran,[37,38] dilute hydrochloric acid[46]).



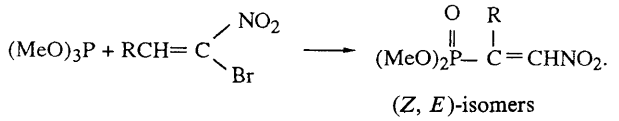
R = Alk. Ar. AlkO; R^1 = Alk; R^2 = Alk. CCl_3; R^3 = H. Br.

The reaction of the full esters of phosphorus(III) acids with 3,3,3-trichloro-1-nitroprop-1-ene proceeds under mild conditions.[47,48]



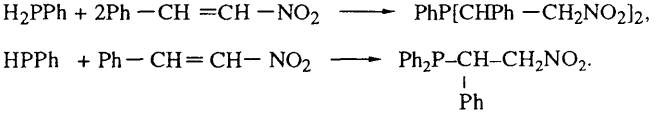
When the product of the interaction of dimethyl trimethylsilyl phosphite with 3,3,3-trichloro-1-nitroprop-1-ene[48] is treated with proton-donating reagents (water, methanol, acetic acid, and hydrogen chloride), dimethyl 2,2-dichloro-1-nitromethylvinylphosphonate (V) is formed together with dimethyl 1-trichloromethyl-2-nitroethylphosphonate (IV). This shows that the presence of the strongly electron-accepting trichloromethyl group at the α-carbon atom of the organophosphorus compound increases significantly the mobility of the α-CH proton, which is able to compete even with the trimethylsilyl group in terms of its capacity for migration. In aprotic solvents, 2,2-dichloro-1-nitromethylvinylphosphoryl derivatives (V) are formed exclusively. Since the chloride anion behaves more readily as a leaving group than the nitrite anion, in this case 1-trichloromethylvinylphosphoryl compounds are not formed. The nitro-derivative (IV) is readily dihydrochlorinated with sodium acetate in ether, affording the product (V).

(*Z*) 1-Bromo-1-nitroalk-1-enes[36,49,50] react with trialkyl phosphite to form nitroalkenylphosphonates. Thus the reaction of trialkyl phosphite with (*Z*)-1-bromo-1-nitro-3-methylbut-1-ene results in the formation of a mixture of the (*Z*)- and (*E*)-isomers of 2-nitroalkenylphosphonates and other compounds.

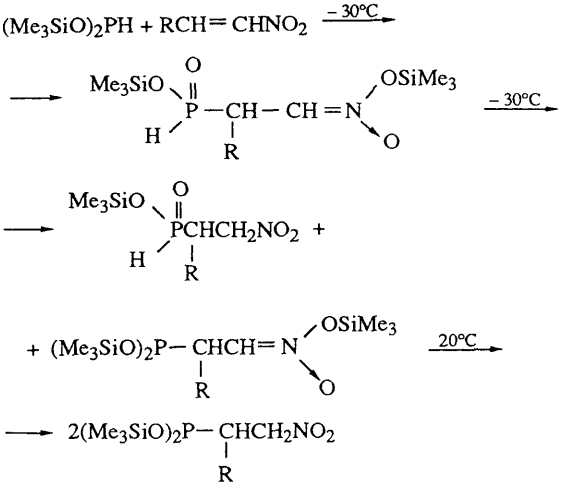


(*Z*, *E*)-isomers

One of the most thoroughly investigated methods of synthesis of organophosphorus β-nitro-compounds involves the nucleophilic addition of hydrophosphoryl compounds to conjugated nitroalkenes. Thus the interaction of phenylphosphine and diphenylphosphine with nitrostyrene leads to the formation of the corresponding di- and mono-adducts.[51]

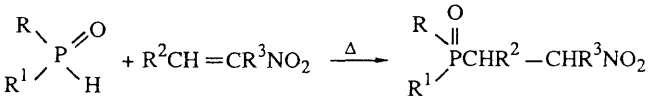


The interaction of bis(trimethylsilyl) hypophosphite with 1-nitroprop-1-ene and nitrostyrene is a multistep process. When the reaction is carried out at temperatures in the range −30 − 35 °C, trimethylsilyl 2-aci-nitroalkylphosphonites are formed. The latter are converted at room temperature into bis(trimethylsilyl) phosphonites.[52]



R = Me. Ph.

Dialkylphosphinties,[53,54] alkyl alkylphosphonates,[54] dimethyl phosphite,[54–56] and diethyl phosphite[57] add to conjugated nitroalkenes after prolonged heating at 100 °C in the absence of catalysts to form organophosphorus β-nitro-compounds.



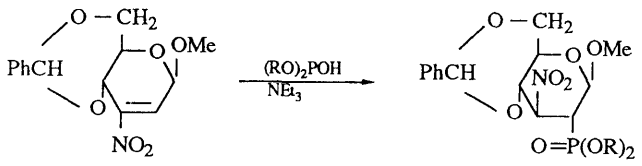
R, R^1 = Ph, $PhCH_2$, C_6H_{13}, OMe; R^2 = Me, Ph, Pr, Et, iso-Pr;

R^3 = H, Me, COOEt.

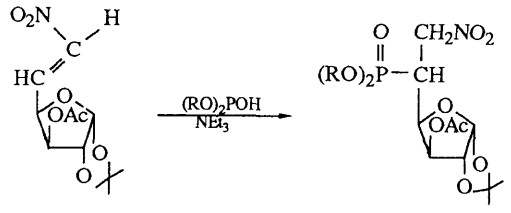
An attempt was first made to carry out this reaction in the presence of basic catalysts, but the competing polymerisation reaction of the nitroalkene reduced the yield of the organophosphorus β-nitro-compound or altogether prevented its formation.[58] The polymerisation of nitroalkenes was partly suppressed by using an excess of dialkyl phosphite and a polymerisation inhibitor.[59]

The addition of dialkyl phosphites to unsaturated nitrosugars is one of the ways of modifying the latter.[60] Phosphonites and phosphines have also been used to modify sugars.[61] Thus the addition of methyl ethylphosphonite to 3-*O*-acetyl-5,6-dideoxy-1,2-isopropylidene-6-*C*-nitro-α-D-xylohex-5-enofuranose takes place on heating at 70 − 80 °C for 7 − 10 h, the yield of the adduct being

90%. When phenylphosphine is used, monoadducts (63%) and diadducts (34%) are formed.[61]

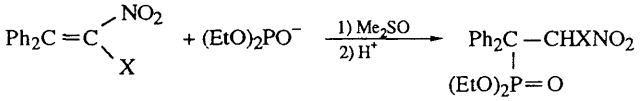


R = Me (69%); Et (3.4%)



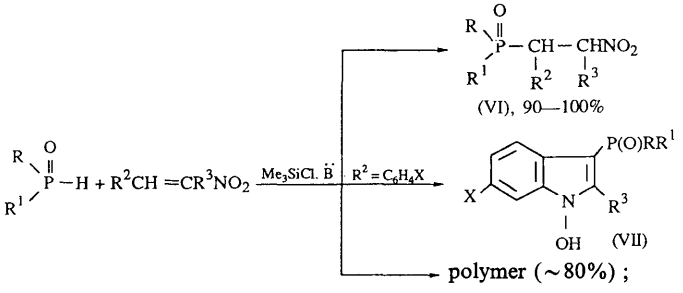
R = Me (43%); Et (3.4%)

The interaction of 1,1-dinitro-2,2-diphenylethene[62] and its derivatives[63] with one equivalent of diethyl phosphite in dimethyl sulphoxide leads to the corresponding adducts on acidification.



X = H, PhS, t-BuS, NO_2.

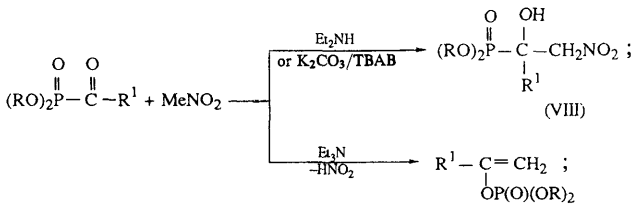
Reactions of partly esterified phosphites with nitroalkenes in the presence of trimethylsilyl chloride and a base, which proceed via a stage involving the formation of dialkyl trimethylsilyl phosphite, lead to organophosphorus β-nitro-compounds in almost quantitative yields.[64] It was later shown that, depending on the nature of the nitroalkene, the reactant ratio, and the reaction conditions, organophosphorus nitro-compounds (VI), *N*-hydroxyindoles (VII), and polymers are formed.[65,66]



R, R^1 = Alk, Ph, AlkO; R^2 = H, Alk, Ph, *p*-HOC_6H_4; R^3 = H, Me.

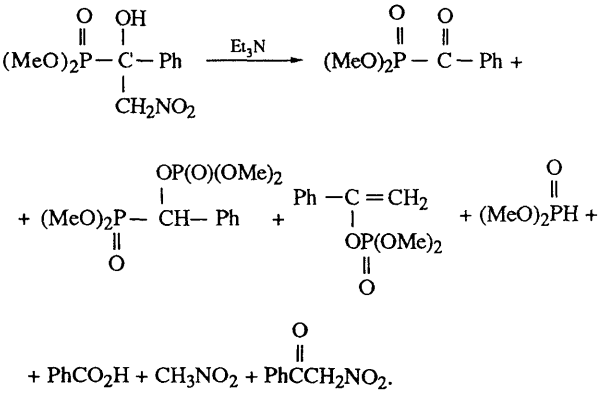
Thus polar solvents promote the formation of the organophosphorus compounds (VI). In terms of their effect on the formation of compounds (VI), the solvents can be arranged in the following sequence : DMF > Me_2CO > MeCN > CH_2Cl_2 > THF > Et_2O > C_6H_6.[65] When aromatic nitroalkenes with electron-donating substituents in the benzene ring, weakly polar solvents, and highly basic acid-binding reagent are used, the reaction proceeds mainly via the pathway leading to the formation of the indole derivative (VII). (The structure of *N*-hydroxyindoles was established by NMR spectroscopy and X-ray diffraction[65]). The formation of the polymeric adduct is promoted by inorganic bases.

The interaction of organophosphorus α-carbonyl compounds with nitroalkanes to form the corresponding organophosphorus β-nitro-compounds (VIII) takes place successfully in the presence of diethylamine and Triton B (OH)[67–69] and also under the conditions of phase transfer catalysis in the K_2CO_3–tetrabutylammonium bromide (TBAB) system.[70] When triethylamine is used, the enol phosphate (IX)—the product of the phosphonate–phosphate rearrangement of compound (VIII)—is formed preferentially.



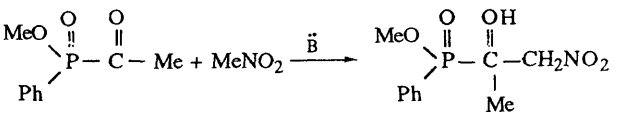
R = Me, Et, iso-Pr; R^1 = Me, Et, Pr, *m*-MeC_6H_4, *o*-MeC_6H_4, *p*-MeC_6H_4, *p*-FC_6H_4, *m*-FC_6H_4, *o*-FC_6H_4, *o*-ClC_6H_4, *p*-ClC_6H_4, $PhCH_2$, $PhCH_2CH_2$, *p*-$FC_6H_4CH_2$, C_6H_{11}.

Apart from the enol phosphate (IX), other products were also identified in the reaction mixture when the reaction was carried out in the presence of triethylamine, which indicates the reversibility of the reaction and the capacity for the cleavage of the C–C and C–P bonds in the initial compound (VIII).[70]

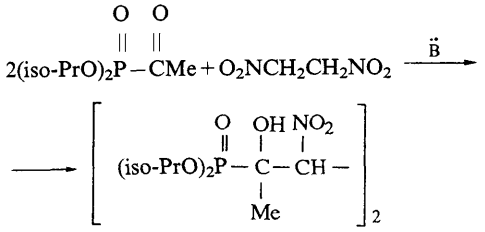


Thermographic studies showed that, in the absence of catalysts, the phosphonate–phosphate rearrangement does not occur, compound (VIII) being decomposed with rupture of the C–P bond and subsequent oxidation.[71]

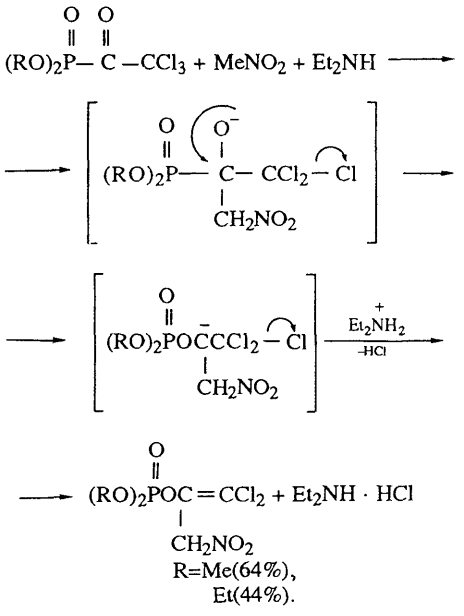
Apart from the α-carbonyl derivatives of phosphonates, acylphosphinates also react with nitroalkanes. Thus the reaction of nitromethane with methyl acetyl(phenyl)phosphinate affords methyl 2-hydroxy-1-nitropropyl(phenyl)phosphinate.[72]



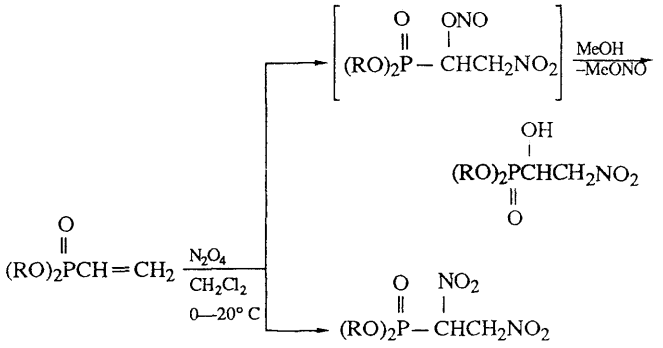
The vicinal dinitroethane reacts with diisopropyl acetylphosphonate in any molar proportions to form only the diadduct.[73]



The reaction of trichloroacetylphosphonate with nitromethane[74] affords the products of the phosphonate–phosphate rearrangement — dialkyl 2,2-dichloro-1-nitromethylvinyl phosphates.



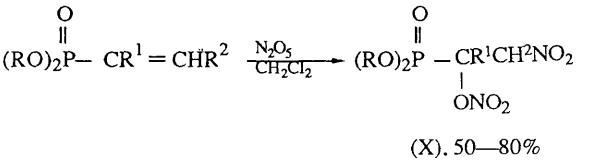
Nitration of unsubstituted vinylphosphonates with dinitrogen tetroxide leads predominantly to dialkyl 1-hydroxy-2-nitroethylphosphonates and dialkyl 1,2-dinitroethylphosphonates in a very low yield.[75,76]



R = Me, Et, iso-Pr, CH_2CH_2Cl.

Alkyl-substituted vinyl phosphonates could not be nitrated.

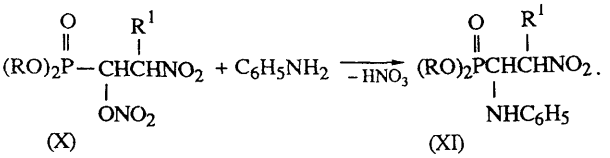
Dinitrogen pentoxide interacts with vinylphosphonates to form the relatively unstable dialkyl 2-nitro-1-nitroxyalkylphosphonates (X).[77] Certain alkyl-substituted vinylphosphonates also enter into this reaction.



(X). 50—80%

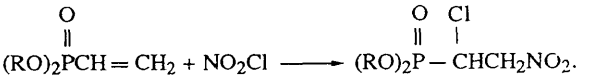
R = Me, Et, iso-Pr, CH_2CH_2Cl' R^1 = H, Me; R^2 = H, Ph.

In the nitration of dimethyl-2-phenylvinylphosphonate with dinitrogen pentoxide, the nitro-group adds to the β-position (δ_P = 21 p.p.m.) , in contrast to its nitration with dinitrogen tetroxide.[77] Compounds (X) react with aniline to form the stable crystalline products (XI):[77]



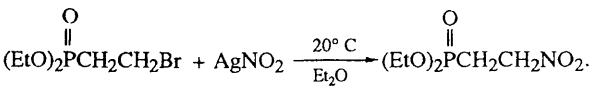
The reaction apparently proceeds via the intermediate formation of nitroalkenes.

The reaction of nitrosyl chloride with dialkyl vinylphosphonate results in the formation of 1-chloro-2-nitroalkylphosphonates.[78]



It is noteworthy that the interaction of nitrosyl chloride with the dichlorides of α-chloro-β-ethoxy- and β-chloro-β-ethoxy-vinylphosphonates and their full esters takes place in a complex manner and does not lead to organophosphorus nitro-compounds.[79]

2-Nitroethylphosphonates are also obtained by Kornblum's method from 2-bromoethylphosphonate and silver nitrite.[80]



2. The structure of organophosphorus β-nitro-compounds

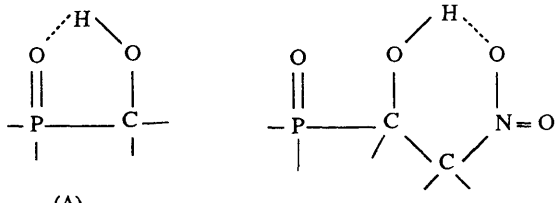
The structure of organophosphorus β-nitro-compounds has been investigated by IR and NMR spectroscopy and by X-ray diffraction.

The ^{31}P chemical shift for β-nitroalkylphosphonates (δ_P = 17–22 p.p.m.) is greater than for α-nitroalkylphosphonates (δ_P = 11–12 p.p.m.), which indicates a decrease in the influence of the nitro-group on the magnetic characteristics of the phosphorus atom.

The absorption bands of the nitro- and phosphoryl groups in the IR spectra of organophosphorus β-nitro-compounds do not differ from the analogous bands in the spectra of organophosphorus and nitro-compounds.

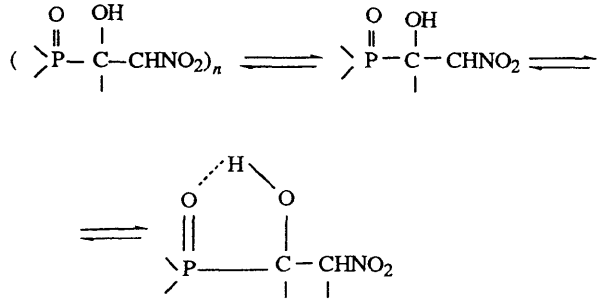
The stereochemistry of α-aryl-β-nitroalkylphosphinates has been studied in greater detail.[66] The compounds were separated by recrystallisation into two pairs of diastereoisomers and the structure of each pair was determined by X-ray diffraction.

The structure of the organophosphorus β-nitroalcohols was also of theoretical interest. On the basis of their geometrical structure, one may postulate the formation of two types of hydrogen bonds: via the phosphoryl oxygen with closure of a five-membered ring [structure (A)] and via the oxygen of the nitro-group with closure of a six-membered ring [structure (B)].



(A) (B)

It has been shown by IR spectroscopy[81] that in the solid state β-nitro-alcohols form intermolecular hydrogen bonds [ν(OH) = 3220–3280 cm^{-1}] between the OH and P=O groups, whereas in solution an equilibrium is established between the free [ν(OH) = 3550 cm^{-1}] and associated molecules of the phosphonates.



In inert solvents, organophosphorus nitroalcohols form an intramolecular hydrogen bond via the oxygen of the phosphoryl group [structure (A)] with a very low interaction energy in the five-membered phosphorus-containing ring.

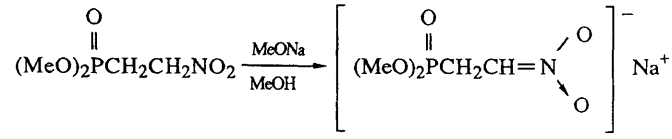
A hindered *gauche*-conformation with a transoid orientation of the phosphoryl and nitro-groups has been established for tertiary organophosphorus nitroalcohols by NMR. It is stable in the temperature range from −40 °C to 100 °C in various solvents.[12]

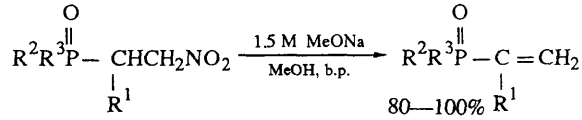
3. Chemical properties of organophosphorus β-nitro-compounds

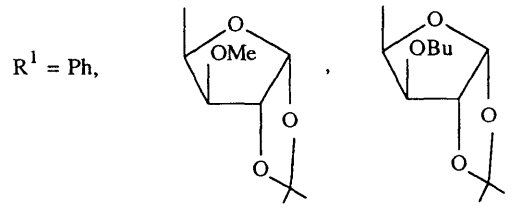
It is natural to expect that chemical reactions involving the nitro-, phosphoryl, and other functional groups as well as isomerisation processes and reactions involving cleavage at the C–P bond are characteristic of organophosphorus β-nitro-compounds.

(a) Reactions with participation of the nitro-group

2-Nitroethylphosphonates are converted into sodium nitronates in the reaction with sodium methoxide in methanol at room temperature,[31] whilst on boiling they afford the corresponding vinylphosphonates, vinylphosphinates, and vinylphosphine oxides.[82]



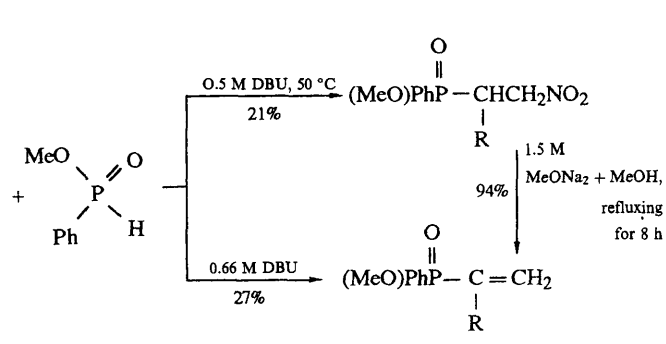


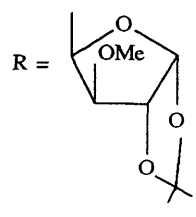


R^2, R^3 = OMe. Ph.

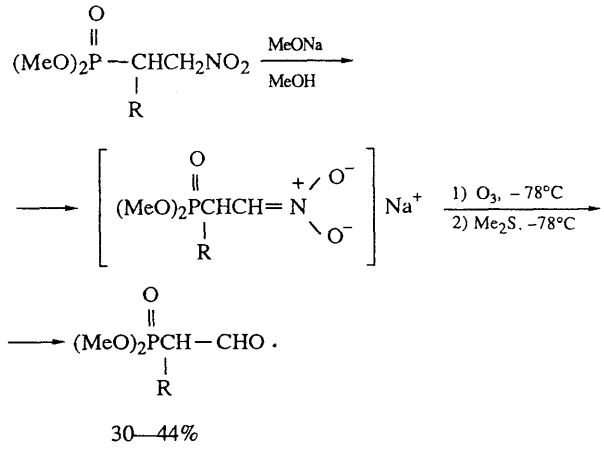
Proton exchange in the sodium methoxide–methanol system has been observed by the ^1H NMR method. It was demonstrated unambiguously that only the hydrogen atom at the β-carbon atom is acidic, whereas this was not observed for the hydrogen atoms at the α-carbon atom.[31]

Nitrovinyl-containing sugars have been converted into vinyl-substituted phosphorus-containing sugar derivatives either by the addition of the hydrophosphoryl compound in the presence of 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) followed by denitration with sodium methoxide or by heating the initial reactants at 60 °C in the presence of DBU.[82]



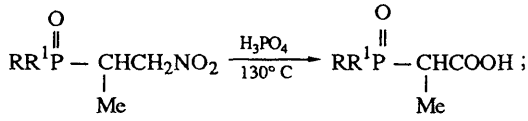


Treatment of sodium nitronate with ozone at −78 °C leads to the corresponding aldehyde:[55,56]



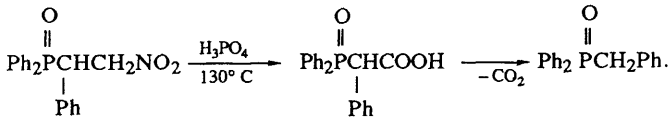
30—44%

When 2-nitroalkylphosphine oxides are heated to 130 °C with 85% orthophosphoric acid, the nitro-group is readily converted into a carboxy-group.[53]

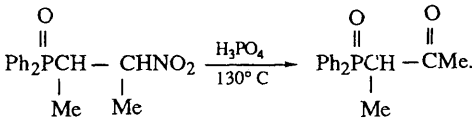


R, R^1 = Ph, $PhCH_2$, C_6H_{13}.

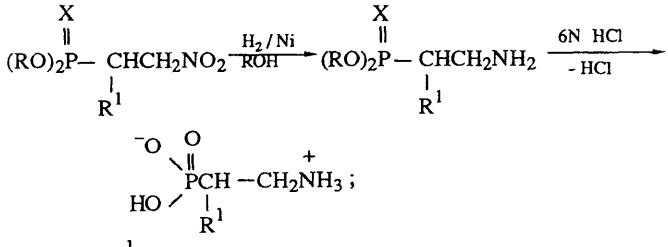
In the presence of a phenyl substituent at the α-carbon atom, the carboxy-group formed on treatment with orthophosphate decarboxylates under the reaction conditions. Thus benzylidiphenylphosphine oxide is formed from β-nitro-α-phenylethyl(diphenyl)-phosphine oxide.[53]



The nitro-group in β-alkyl-substituted 2-nitroalkylphosphine oxides is converted into a keto-group under analogous conditions.[53]

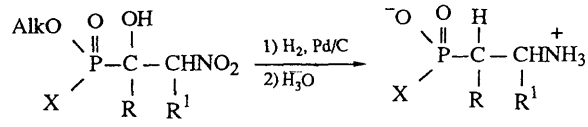


Organophosphorus β-nitro-compounds are reduced with hydrogen in the presence of the Raney nickel catalyst.[59,83,84] Subsequent acid hydrolysis of the 2-amino-derivatives leads to the corresponding aminoacids.



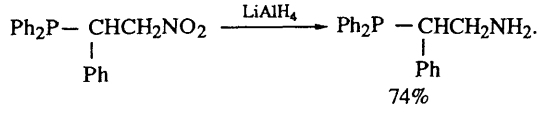
R = Alk; R^1 = Alk, Ph; X = O. S.

The reduction of 1-hydroxy-2-nitroalkylphosphonates with hydrogen in the presence of Raney nickel is accompanied by their partial decomposition at the C—P and C—C bonds.[72,85] Hydrogenation on palladium catalysts[72,86] or on Raney nickel in the presence of acetic acid[87] is more suitable. The reduction products are either isolated as picrates or are converted by acidic hydrolysis into the corresponding acids.[72,86–88]

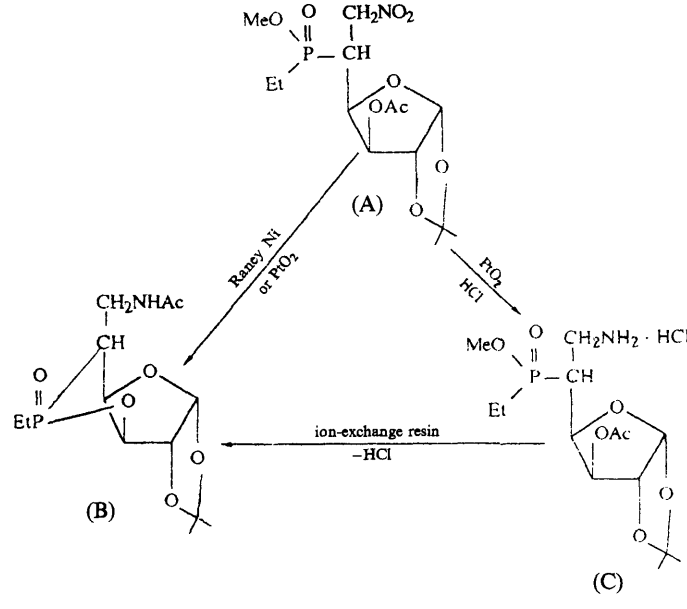


R, R^1 = Alk, Ph; X = OAlk, OH, Ph.

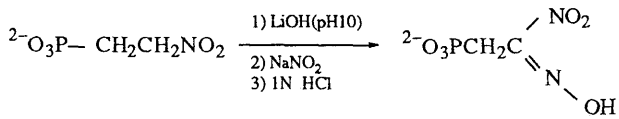
Lithium tetrahydroaluminate reduces 2-nitro-1-phenylethyl-(diphenyl)phosphine to the corresponding amine.[51]



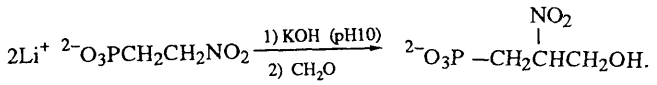
However, in the reduction of nitrosugars—for example, 3-*O*-acetyl-5,6-dideoxy-5-*C*-[ethyl(methoxy)phosphinyl]-1,2-*O*-isopropylidene-6-*C*-nitro-α-D-glucofuranose (A)—with lithium tetrahydroaluminate or with sodium dihydrobis(2-methoxyethoxy)-aluminate (SDMA), the sugar derivatives are decomposed. The reduction of compound (A) with hydrogen in the presence of Raney nickel affords a 69% yield of crystalline 6-acetamido-5-(3-*O*-cyclophosphinato)-5,6-dideoxy-1,2-*O*-isopropylidene-α-*D*-glucofuranose (B). In order to rule out cyclisation and the transfer of the acetyl group, compound (A) is reduced in the presence of hydrochloric acid in methanol using platinum oxide as the catalyst. The latter reaction leads to the formation of the unstable hydrochloride of 3-*O*-acetyl-6-amino-5,6-dideoxy-5-*C*-[ethyl(methoxy)phosphinyl]-1,2-*O*-isopropylidene-α-D-glucofuranose (C) in 80% yield. When compound (C) is treated with an ion-exchange resin in methanol, it is converted into compound (B).[61]



2-Phosphonoethylnitronic acid can be obtained by Mayer's method—by treating 2-nitroethylphosphonic acid with sodium nitrite at pH 10 (lithium hydroxide) on ice with subsequent slow acidification with 1 M solution of hydrochloric acid.[80]

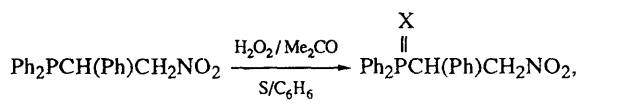


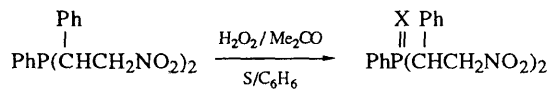
The lithium salt of 2-nitroethylphosphonic acid combines with two equivalents of formaldehyde at pH 10, affording 3-hydroxy-2-nitropropylphosphonic acid.[80]



(b) Reactions of the phosphorus-containing group

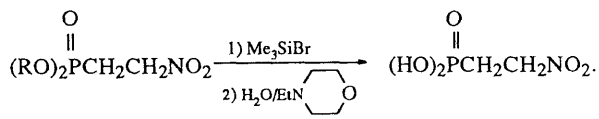
β-Nitro-derivatives of trivalent phosphorus are readily oxidised by a solution of hydrogen peroxide in acetone to *P*-oxides or are converted into *P*-sulphides on treatment with sulphur in benzene.[51]





X = O, S.

Dialkyl 2-nitroalkylphosphonate can be converted into the free acid by treatment with bromotrimethylsilane and subsequent hydrolysis of the resulting bis(trimethylsilyl) 2-nitroethylphosphonate with 0.5 M solution of *N*-ethylmorpholine.[80]



After the neutralisation of the reaction mixture with 1 M HCl solution, 85% of the nitro-groups remain unhydrolysed.

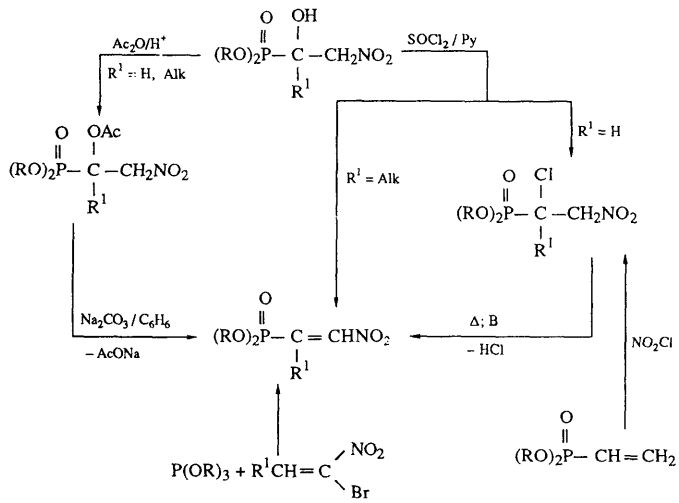
(c) Other reactions

The synthesis and properties of 2-nitrovinylphosphonates. The first representatives of 2-nitrovinylphosphonates were synthesised by deacetylating the acetyl derivatives of organophosphorus nitroalcohols[68] and by dehydrohalogenating 1-chloro-2-nitroalkylphosphonates.[78] Several representatives of 1-alkyl-substituted nitrovinylphosphonates have been obtained by the reaction of trialkyl phosphites with conjugated *gem*-bromonitroalkenes.[36,50]

The present authors investigated in detail the possibilities of the synthesis of 2-nitroalkenylphosphonates from organophosphorus nitroalcohols and nitronitrates.[89]

Direct dehydration of β-nitroalcohols with diphosphorus pentoxide or phthalic anhydride proved to be impossible owing to the low strength of the C–P bond. The acetyl derivatives of β-nitroalcohols are therefore formed initially, their deacetylation occurring readily in inert solvents in the presence of sodium carbonate.[68]

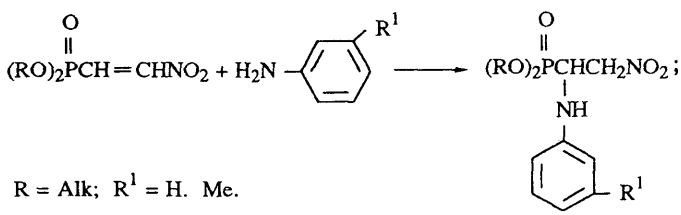
Thionyl chloride reacts with tertiary organophosphorus nitroalcohols in the presence of pyridine, affording satisfactory yields of nitrovinylphosphonates, while its reaction with secondary organophosphorus nitroalchols gives rise to 1-chloro-2-nitroalkylphosphonates which are isolated by column chromatography. On the other hand, chloronitroalkylphosphonates split off hydrogen chloride during distillation and on treatment with organic bases, forming the corresponding nitrovinylphosphonates in a low yield.[89]



It has been shown by ^{1}H and ^{31}P NMR spectroscopy that 2-nitrovinylphosphonates give rise predominatly to the (*E*)-isomers.

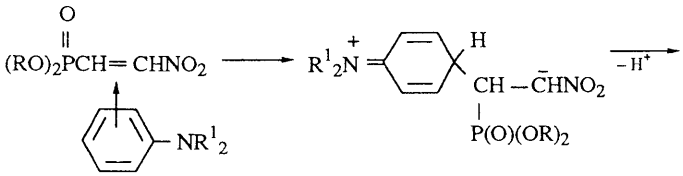
Nucleophilic reactions of 2-nitrovinylphosphonates. Condensation of 2-nitrovinylphosphonates with many nucleophiles and their involvement in the diene synthesis[90] have expanded their synthetic possibilities.

Aromatic amines (aniline, *m*-toluidine) readily add to 2-nitrovinylphosphonate in acetic acid, affording the corresponding products in satisfactory yields.[90]

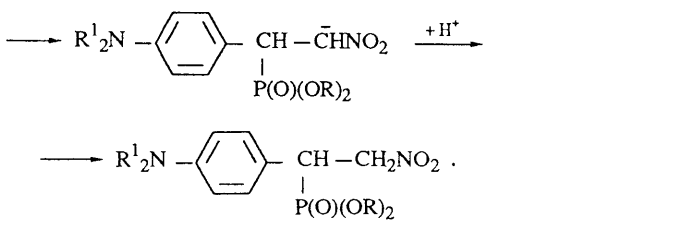


R = Alk; R^1 = H, Me.

It has been observed that 2-nitrovinylphosphonates are arylated by *N,N*-dialkylanilines.[90]

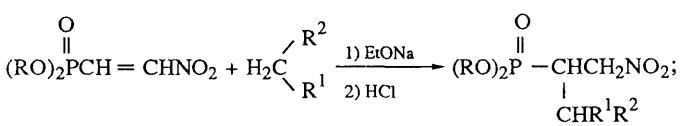


π-complex σ-complex



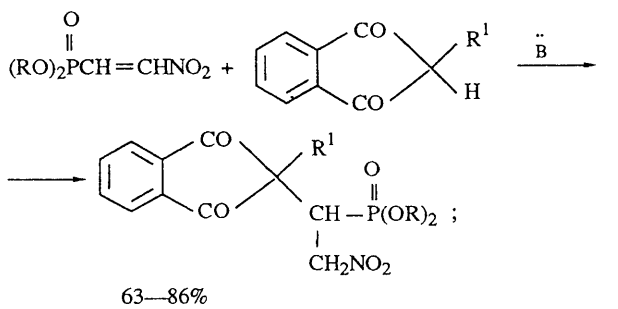
The reaction apparently proceeds via stages involving the formation of π- and σ-complexes.

The general mechanism of the addition of aliphatic CH acids to nitrovinylphosphonates can be represented as follows:[90,91]



R = Alk; R^1. R^2 = H. COOAlk. CN. NO_2. C(O)Me.

The conditions for the addition of β-diketones to 2-nitrovinylphosphonates depend on the structure of the β-diketones.

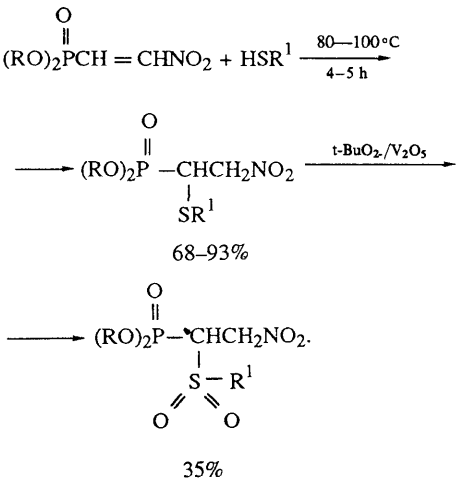


63—86%

R = Alk; R^1 = H, Ph, *p*-$MeOC_6H_4$, MeCO.

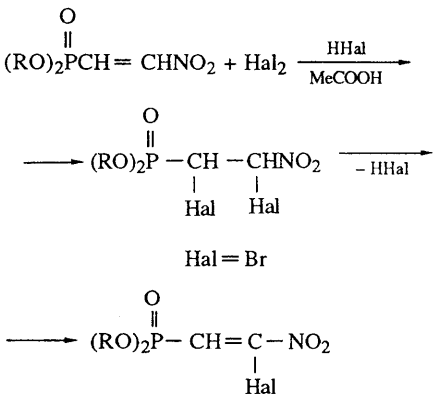
It has been established[90,92] that β-diketones which do not enolise in their usual state (indan-1,3-dione, 2-phenylindan-1,3-dione, 2-anisylindan-1,3-dione, and 2-acetylindan-1,3-dione) react with 2-nitrovinylphosphonate in aprotic solvents (benzene) in the presence of triethylamine, i.e. under conditions suppressing enolisation according to Mayer's inverse rule,[93] whereas enolisable β-diketones (dimedone, barbituric acid) react in the presence of sodium ethoxide in ethanol, i.e. under conditions promoting enolisation in conformity with Mayer's inverse rule.

Alkanethiols interact with organophosphorus nitroalkenes on heating in a sealed tube.[90,94] The reaction apparently proceeds via a radical mechanism. The organophosphorus nitrosulphides formed as a result are oxidised to the corresponding sulphones by t-butyl peroxide in the presence of divanadium pentoxide.



35%

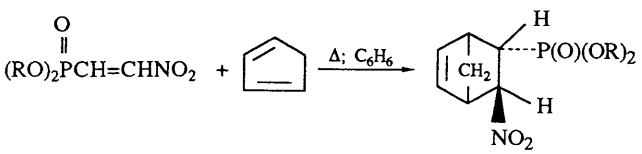
The increased nucleophilicity of the double bond in 2-nitrovinylphosphonates permits their halogenation only under the conditions of nucleophilic addition, namely in acetic acid in the presence of a hydrogen halide as the catalyst.[90]



Hal = Cl. Br.

In the bromination of an organophosphorus nitroalkene, it is possible to obtain in the first stage an adduct, which after isolation and during storage is gradually converted into a bromonitroalkenylphosphonate. However, on chlorination of the nitroalkene, the intermediate could not be isolated.

The reaction with cyclopentadiene takes place stereospecifically for 2-nitrovinylphosphonate with retention of the(*E*)-configuration.[91]

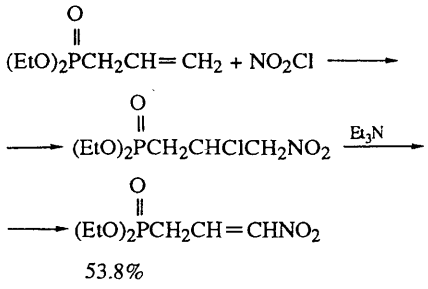


IV. Organophosphorus γ-nitro-compounds

Organophosphorus γ-nitro-compounds are interesting as precursors of phosphonic analogues of γ-aminobutyric acid, which exhibit a broad spectrum of biological activity.[95]

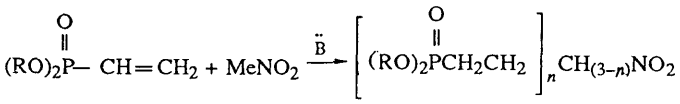
1. Synthesis of organophosphorus γ-nitro-compounds

The addition of nitryl chloride to diethyl allenylphosphonate and subsequent dehydrochlorination of the adduct with triethylamine lead to nitroallenylphosphonate.[78]



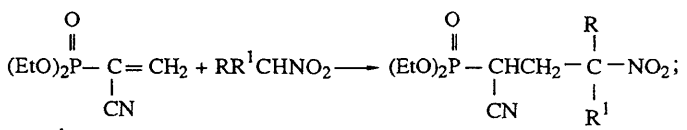
53.8%

Nitromethane adds to vinylphosphonates under the conditions of the Michael reaction with formation of mono-, di-, and tri-adducts. The monoadduct was obtained by the reaction of nitromethane with diethylvinylphosphonate.[96,97] However, di-(2-chloroethyl) vinylphosphonate reacts with nitromethane to form predominantly di- and tri-adducts, which were isolated by column chromatography.[90]



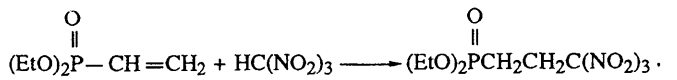
R = Et. n = 1 (37%); R = CH_2CH_2Cl. n = 2 (70%); n = 3 (9%).

Diethyl 1-cyanovinylphosphonate also combines actively with nitroalkanes under the conditions of the Michael reaction.[98]

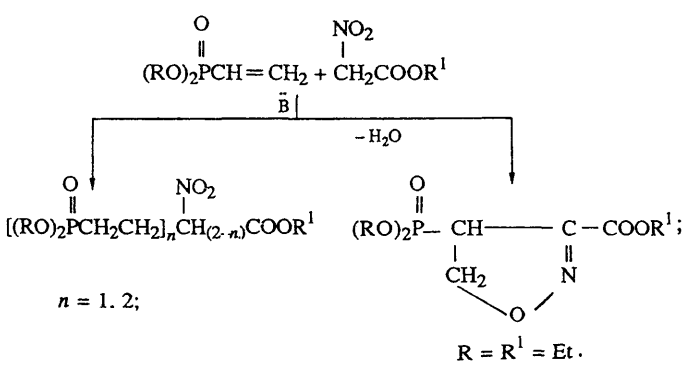


R, R^1 = H, Me.

Trinitromethane reacts with diethyl vinylphosphonate in ether without a catalyst at room temperature.[99]



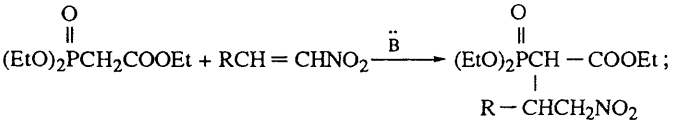
Nitroacetic ester reacts with vinyl phosphonates under the conditions of the Michael reaction, affording either mono- and di-adducts or dihydroisoxazole depending on the nature of the aklkoxy-substituents at the phosphoryl and carbonyl groups.[90]



n = 1. 2;

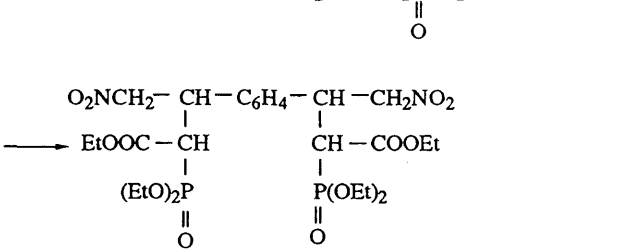
R = R^1 = Et.

Triethyl phosphonacetate adds to 1-nitroalkenes in the presence of bases to form organophosphorus γ-nitro-compounds.[58,59]

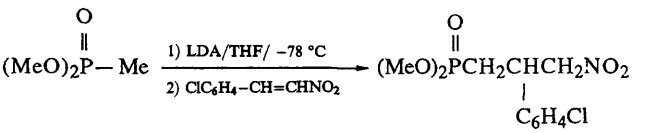


R = Me, iso-Pr.

The interaction of triethyl phosphonacetate with *p*-di(β-nitrovinyl)-benzene leads to a crystalline diadduct.[100]

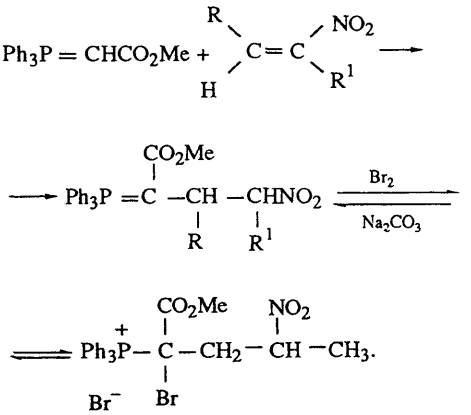


As a weak CH acid, dimethyl methylphosphonate reacts with nitroalkenes only in the presence of a superbase—lithium diisopropylamide.[101]



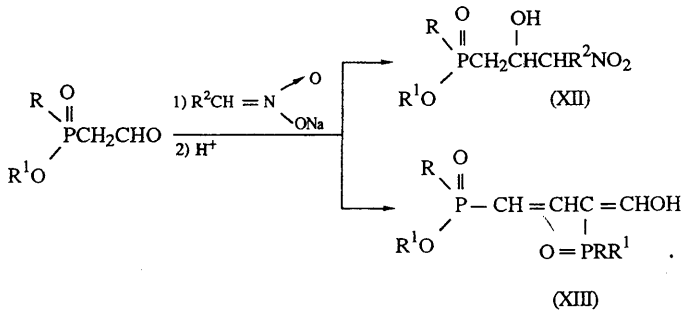
71%

Methoxycarbonylmethylenetriphenylphosphorane (a CH acid) reacts with conjugated nitroalkenes at 90 °C to form ylides—methoxycarbonylalkylidenetriphenylphosphoranes.[102,103]



The preferential formation of ylides rather than a phosphonium salt in this reaction has been demonstrated by bromination.

Organophosphorus β-aldehydes react with nitroalkanes in the presence of bases to form β-hydroxy-γ-nitro-derivatives (XII), which were isolated by molecular distillation.[104] The reaction is accompanied by aldol self-condensation to compound (XIII).



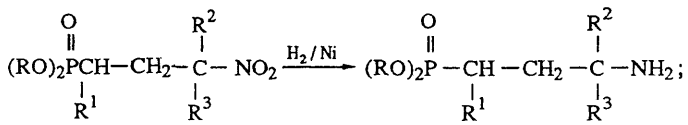
(XIII)

Organophosphorus γ-nitroalcohols (XII) form associated species characterised in the IR spectra by an OH absorption band in the range 3229–3267 cm^{-1}. On dilution with non-polar solvents and also on raising the temperature, the associated species decompose into monomers with intramolecular OH...O=P [ν(OH) = 3320–3400 cm^{-1}] and OH...O_2N [ν(OH) = 3488–3550 cm^{-1}] hydrogen bonds.

2. Chemical reactions of organophosphorus γ-nitro-compounds

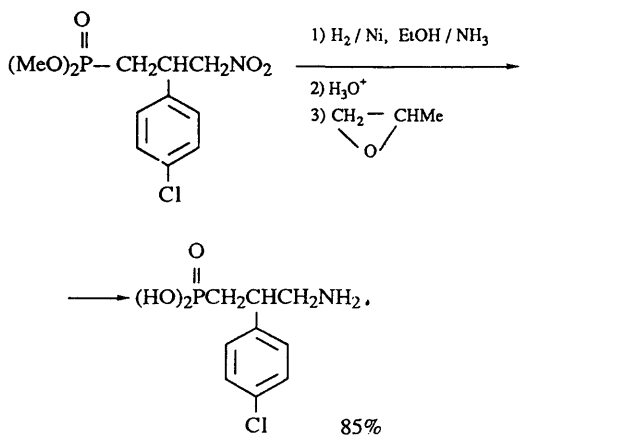
The chemical reactions of organophosphorus γ-nitro-compounds are predominantly reduction reactions.

Amino-derivatives are obtained by hydrogenating nitro-compounds in the presence of Raney nickel. In most cases they were isolated as the picrates.[83]



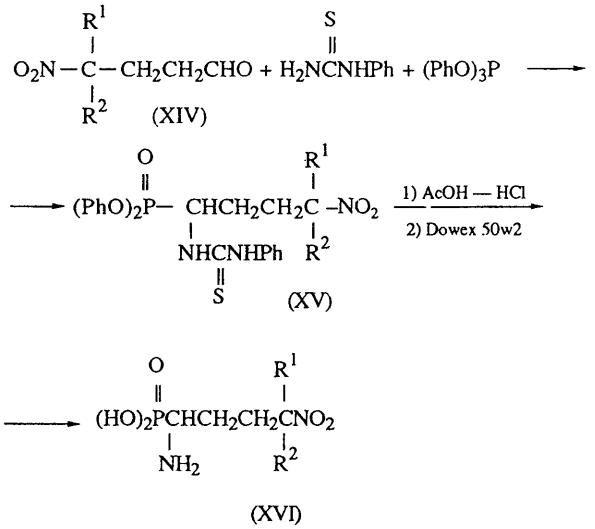
R = Et; R^1 = H, CN; R^2 = H, Me; R^3 = H, Me.

3-Aminopropylphosphonic acid was synthesised by condensing nitromethane with diethyl vinylphosphonate and subsequent reduction and hydrolysis.[97] (±)-3Amino-2-(4-chlorophenyl)propylphosphonic acid (phaclofen)—an antagonist of γ-aminobutyricacid (GABA)—is obtained similarly from the adduct resulting from the addition of dimethylmethylphosphonate to β-nitrostyrene.[101]



V. Organophosphorus δ-nitro-compounds

The condensation of nitroaldehydes (XIV) with triphenyl phosphite and phenylthiourea followed by decomposition of complexes (XV) by acid hydrolysis leads to α-amino-δ-nitroalkylphosphonic acids (XVI).[105]

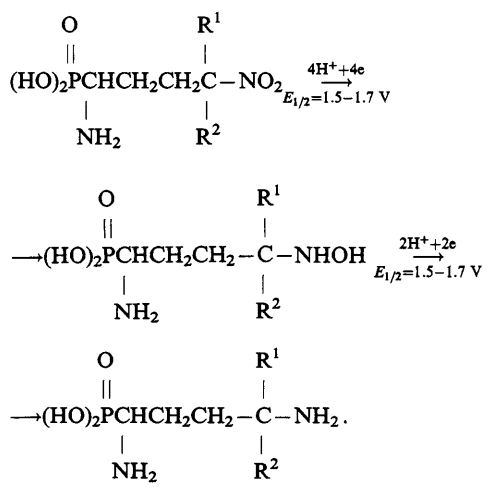


(XVI)

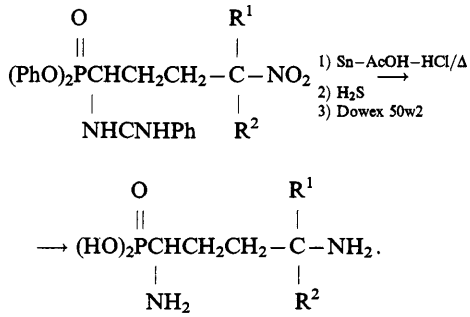
Compound	R^1	R^2	Yield of (XV), %	Yield of (XVI), %
a	H	H	72	10
b	Me	H	75	10
c	Me	Me	70	60

The acid hydrolysis of the nitro-compound (XVc), which contains no hydrogen atoms in the *gem*-positions relative to the nitro-group, takes place more successfully (60%). The hydrolysis of other nitro-derivatives is apparently accompanied by the Nef reaction.

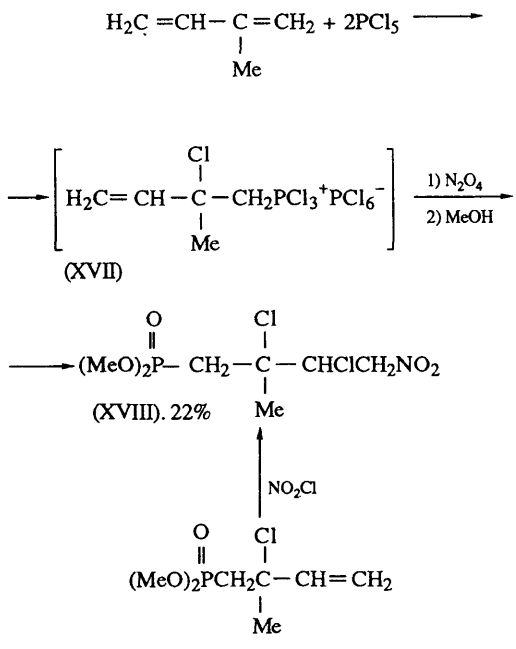
Compound (XVI) is reduced electrochemically initially to α-amino-δ-hydroxyamino-derivatives and then to α, δ-diaminoalkylphosphonic acids.[105]



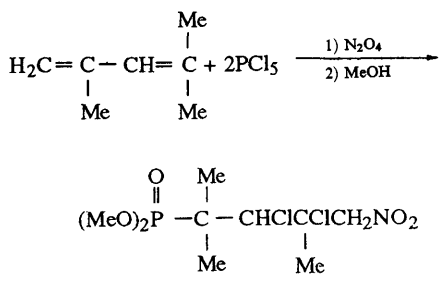
The reduction of diphenyl phosphonates (XV) with tin in the presence of acetic and hydrochloric acids affords in one stage α, δ-diaminoalkylphosphonic acids.[105]



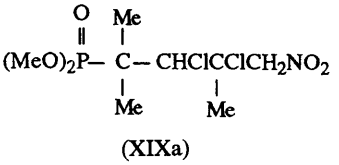
The decomposition with dinitrogen tetroxide of the complex between phosphorus pentachloride and isoprene (XVII) at 0 °C in an inert solvent with subsequent esterification is completed by the synthesis of dimethyl 2,3-dichloro-2-methyl-4-nitrobutylphosphonate (XVIII).[106–108] The structure of the product (XVIII) was confirmed by unambiguous synthesis.



The complex of 2,4-dimethylpenta-1,3-diene and phosphorus pentachloride reacts with dinitrogen tetroxide under analogous conditions to form dimethyl 3,4-dichloro-2,4-dimethyl-5-nitropentylphosphonate (XIXa).[107]

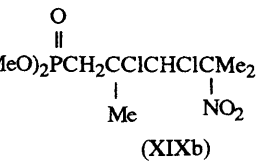


The δ_P = 16 p.p.m. signal in the ^{31}P NMR spectrum of the product (XIXa) confirms the postulated structure. On the other hand, nitrochlorination with nitryl chloride of the ester obtained form 2,4-dimethylpenta-1,3-diene and PCl_5 affords a mixture of the isomers (XIXa) and (XIXb) according to ^{31}P NMR data.



(XIXa)

δp = 16 p.p.m.

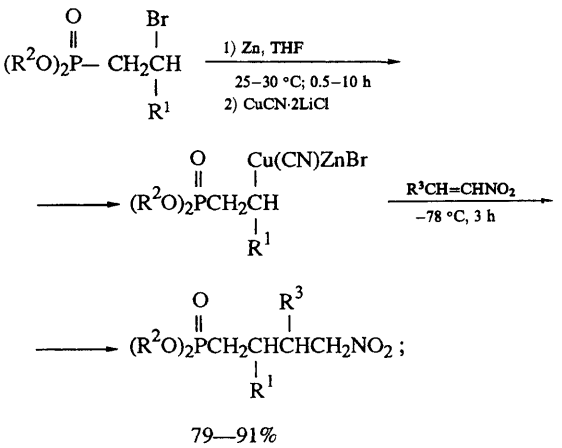


(XIXb)

δp = 26 p.p.m.

The formation of one isomer in the first case can be explained by the greater stability of compound (XIXa), containing a tertiary phosphonate group, in the stage involving the decomposition of the complex with dinitrogen tetroxide.

Certain zinc- and copper-containing β-metal-substituted alkylphosphonates also give rise to organophosphorus δ-nitro-compounds on reaction with nitroalkenes.[109]



R^2 = H, Me, Et, Pr; R^1 = Me, Et; R^3 = Pr, Ph.

VI. Conclusion

Analysis of data on aliphatic organophosphorus nitro-compounds shows that the relative positions of the phosphoryl and nitro-groups influence significantly the choice of reactions for the synthesis of such compounds and also determine their chemical properties. Thus organophosphorus α-nitro-compounds are obtained by nitrating the corresponding alkoxyvinylphosphonates with acetyl nitrate, while organophosphorus β-nitro-compounds are obtained by nitrating vinylphosphonates with dinitrogen tetroxide or pentoxide.

It has been established that trivalent phosphorus (P^{III}) compounds can scarcely be used for the synthesis of organophosphorus α-nitro-compounds, whereas the reactions of dialkyl and trialkyl phosphites with conjugated nitroalkenes have been used successfully to synthesise organophosphorus β-nitro-compounds. Reactions involving addition to 2-nitrovinylphosphonates are of special interest for the synthesis of various organophosphorus β-nitro-compounds containing functional-group substituents. The high electrophilicity of 2-nitrovinylphosphonates is manifested by their ability to alkylate *N,N*-dialkylanilines in the *para*-position in the aromatic ring.

Organophosphorus γ-nitro-compounds are obtained as a rule by the nucleophilic addition of nitroalkanes to vinylphosphonate or of phosphorus-containing CH acids to nitroalkenes. Only specific reactions are used for the synthesis of organophosphorus δ-nitro-compounds, for example, the reaction of nitroaldehydes with triphenyl phosphite and phenylthiourea.

Among all types of organophosphorus nitro-compounds, only α,α-disubstituted α-nitroalkylphosphonates readily withstand acid hydrolysis and conversion into acid chloride on treatment with phosphorus pentachloride. The capacity of aliphatic organophosphorus nitro-compounds for reduction opens a new way to the synthesis of aminoalkylphosphonic acids with functional-group substituents which are difficult to obtain otherwise but are of interest as biologically active compounds.

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