ARBUZOV REARRANGEMENT IN THE REACTION OF ARYLMETHYLENEMALONALDEHYDES WITH TRIMETHYL PHOSPHITE: FORMATION OF 2-(α-DIMETHOXYPHOSPHONYL-BENZYL)-3-METHOXYACROLEINS

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Reaction of arylmethylenemalonaldehydes *I* with trimethyl phosphite affords substituted methoxyacroleins *V*. The reaction proceeds *via* intermediates *VII* which, according to spectral data, can be described as interconverting dipolar and cyclic structures *VIIA* and *VIIB*, respectively. The intermediates *VII* are easily hydrolyzed to give the substituted malonaldehydes *VI*. Compounds *VI* were also obtained by acid-catalyzed hydrolysis of methoxyacroleins *V*.

Recently, we have described[1] the reaction of arylmethylenemalonaldehydes with tributylphosphine which, like other so-called organic Lewis acids[2], give products of dipolar structure *II* (refs[3-5]). In principle, the reaction of arylmethylenemalonaldehydes with trimethyl phosphite may be more complex because the primary products arising from organic Lewis acids and trimethyl phosphite undergo further transformations. In the reaction of trimethyl phosphite with phenylmethylenemalononitrile the methyl group migrates under formation of the phosphonate *III* (ref.[6]) whereas with 3-phenylmethylene-2,4-pentanedione the cyclic phosphorane *IV* was obtained[7].
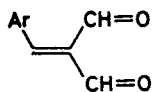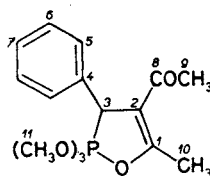

I
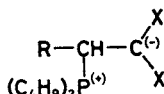
II, X = —CN, —CO—O—C(CH₃)₂—O—CO—,
   —COCH₃, —CHO
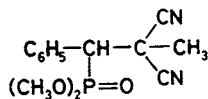
III

IV

It has been proven that under certain conditions (temperature, substitution type of the phosphorus atom) there is an equilibrium between cyclic structure and the open-chain dipolar form[8].

As the first stable product in the reaction of arylmethylenemalonaldehydes with trimethyl phosphite we isolated the methoxyacroleins V. These compounds were hydrolyzed in an acidic medium to give the corresponding malonaldehydes VI (for yields, elemental analyses and melting points of compounds V and VI see Table I, their ^{1}H NMR spectra are given in Tables II and III). However, a closer study has shown that the reaction proceeds *via* an unstable intermediate of the type VII (Scheme 1). Its existence has been proven on the basis of spectral as well

TABLE I

Preparation and properties of methoxyacroleins V and malonaldehydes VI

Compound	M.p., °C (yield, %)	Formula (mol. wt.)	Calculated/found	
			% P	% X
Va	103—106 (53)	$C_{13}H_{16}NO_7P$ (329·3)	9·41 9·35	4·25[a] 4·12
Vb	85—88 (77)	$C_{13}H_{16}ClO_5P$ (318·7)	9·72 9·76	11·12[b] 11·24
Vc	89—91 (72)	$C_{14}H_{19}O_6P$ (314·3)	9·85 9·65	— —
Vd	148—150 (77)	$C_{15}H_{22}NO_5P$ (327·3)	9·46 9·01	4·28[a] 4·06
Ve	95—97 (81)	$C_{11}H_{15}O_5PS$ (290·3)	10·67 10·78	11·04[c] 11·21
VIa	123—127 (77)	$C_{12}H_{14}PO_7N$ (315·2)	9·82 9·89	4·44[a] 4·15
VIb	125—128 (90)	$C_{12}H_{14}ClO_5P$ (304·7)	10·16 10·35	11·63[b] 11·73
VIc	115—118 (97)	$C_{13}H_{17}PO_6$. (300·3)	10·31 10·54	— —
VId	80—94 (63)	$C_{14}H_{20}NO_5P$ (313·3)	9·88 10·08	4·47[b] 4·44
VIe	114—117 (99)	$C_{10}H_{13}O_5PS$ (276·2)	11·21 11·29	11·61[c] 11·51

[a] % N; [b] % Cl; [c] % S.
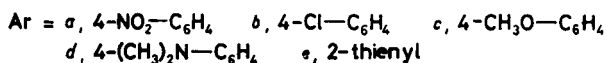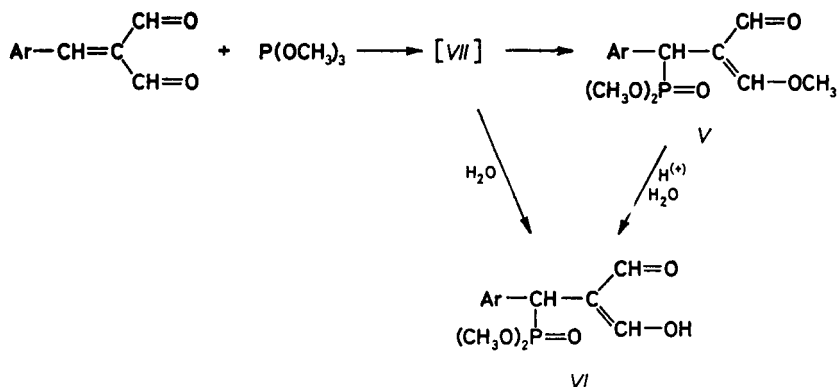
SCHEME 1

as chemical evidence. Intermediates *VII* have characteristic ^{1}H, ^{31}P, and ^{13}C NMR spectra differing from those of the final reaction products *V* (Tables III – V). Treatment of *VII* with water results in instantaneous formation of the malonaldehydes *VI*; under these conditions the methoxyacroleins *V* are stable. The intermediates *VII* can be assigned the dipolar structure *VIIA* or the cyclic structure *VIIB* with pentavalent phosphorus atom. On longer standing or heating, the methyl group migrates

TABLE II
Selected ^{1}H and ^{31}P NMR parameters of methoxyacroleins *Va— Ve* in deuteriochloroform at 60 MHz

Parameter	*Va*	*Vb*[a]	*Vc*[b]	*Vd*[c]	*Ve*
δ(H-1)	9·25 s	9·23 s	9·23 s	9·22 s	9·26 s
δ(H-3)	4·76 d	4·64 d	4·61 d	4·55 d	4·98 d
δ(H-4)	7·14 d	7·07 d	7·02 d	6·98 d	6·80— 7·25 m
δ(C—OCH$_3$)	4·01 s	4·01 s	3·99 s	3·95 s	4·01 s
δ(P—OCH$_3$)	3·69 d	3·69 d	3·68 d	3·57 d	3·69 d
^2J(P, H-3)	27·0	26·5	27·0	26·5	27·5
^3J(P, OCH$_3$)	11·0	10·9	11·0	11·0	11·0
^4J(P, H-4)	2·5	2·5	2·5	2·0	—[d]

[a] $\delta(^{31}$P$) = +26·9$ *vs* H$_3$PO$_4$ ext.; [b] C$_6$H$_4$—OCH$_3$: 3·77 s; [c] N(CH$_3$)$_2$: 2·89 s; [d] value not determined.

TABLE III

Selected ^1H and ^{31}P NMR parameters for compounds IV, VIa—VIe, and VIIb in deuteriochloroform at 200 MHz

| Parameter	IV^a	VIa	$VIb^{b,c}$	VIb^d	VIc	VId	VIe	$VIIb^{b,e}$	$VIIb^d$
δ(H-1)	—	9·08 bs	8·25 bs	7·45 bs	9·16 bd	9·06 bs	9·18 bs	8·65 bs	8·10 bs
δ(H-3)	4·13 dq	4·82 d	4·66 d	4·66 d	4·63 d	4·51 d	5·03 d	4·18 d	4·19 d
δ(H-4)	—	8·16 bs	8·25 bs	9·18 bs	7·37 bs	7·19 bs	7·34 bs	8·65 bs	9·31 bs
δ(OH)	—	12·26 bs	9·97 bs	12·61 bs	12·48 bs	$—^f$	12·16 bs	—	—
δ(OCH$_3$)	3·48 d	3·54 d	3·48 d	3·46 d	3·43 d	3·68 d	3·60 d	3·56 d	3·57 d
	3·48 d	3·82 d	3·77 d	3·81 d	3·77 d	3·72 d	3·77 d	3·56 d	3·57 d
	—	—	—	—	—	—	—	3·56 d	3·57 d
^2J(P, H-3)	23·2	26·0	25·7	25·9	25·6	25·6	25·4	19·5	19·4
^3J(P, OCH$_3$)	12·5	10·9	10·7	10·7	10·6	11·0	10·7	12·5	12·5
	12·5	11·2	11·1	11·0	10·9	11·8	11·1	12·5	12·5
	—	—	—	—	—	—	—	12·5	12·5

^{a} ^{31}P NMR −29·7 ppm vs H$_3$PO$_4$ ext. (ref.[7] gives −27·9 ppm); ^{b} at 328 K; ^{c} ^{31}P NMR (293 K) +33·4 ppm vs H$_3$PO$_4$ ext.; ^{d} at 243 K; ^{e} ^{31}P NMR (293 K) −13·2 ppm vs H$_3$PO$_4$ ext.; ^{f} value not determined.

to the oxygen atom of the malonaldehyde system. So far, no similar rearrangement to the oxygen atom in organic Lewis acids has been observed. We clarified the structure of the isolated primary adduct of trimethyl phosphite with 4-chlorophenylmethylenemalonaldehyde *VIIb* (unstable crystals, m.p. 45 − 50°C).
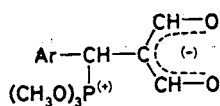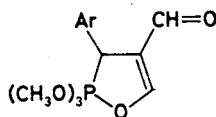
VII A   *VII B*

TABLE IV
^{13}C NMR chemical shifts and ^{13}C–^{31}P coupling constants of compounds *IV*, *Vb*, *VIb*, and *VIIb* in deuteriochloroform[a]

Parameter	*IV*	*Vb*	*VIb*	*VIIb*
δ(C-1)	136·92 d	189·01 dd	190·11 bs	175·50 bs
δ(C-2)	112·72 d	118·65 d	116·48 s	120·60 d
δ(C-3)	47·67 dd	36·86 dd	37·13 dd	41·60 dd
δ(C-4)	194·88 d	170·65 dd	169·54 bs	175·50 bs
δ(C-5)	166·65 d	133·45 d	133·18 d	134·01 d
δ(C-6)	128·65 dd	130·57 dd	130·36 dd	129·77 dd
δ(C-7)	126·55 dd	127·79 dd	128·87 dd	128·13 dd
δ(C-8)	128·11 dd	132·28 d	133·66 d	130·85 d
δ(P—OCH$_3$)	54·93 dq	52·26 dq	53·58 dq	55·43 dq
	54·93 dq	52·97 dq	54·82 dq	55·43 dq
	54·93 dq	—	—	55·43 dq
δ(C—OCH$_3$)	—	62·72 q	—	—
^1J(P, C-3)	159·5	144·4	140·9	158·2
^2J(P, C-2)	10·1	4·5	0·0	11·5
^2J(P, C-5)	11·4	5·1	5·1	9·9
^2J(P, OCH$_3$)	9·3	7·1	7·5	10·8
	9·3	6·8	7·3	10·8
	9·3	0·0	—	10·8
^3J(P, C-1)	9·1	6·0	—[b]	—[b]
^3J(P, C-4)	21·8	7·0	—[b]	—[b]
^3J(P, C-6)	7·5	7·6	6·5	8·5
^4J(P, C-7)	3·7	2·5	2·2	3·6
^5J(P, C-8)	4·6	2·5	3·5	7·5

[a] The signal of solvent was used as internal standard, $\delta(^{13}C^2HCl_3) = 77·0$; [b] value of coupling constant not determined.

The ^{31}P NMR spectrum of *VIIb* exhibits a signal at $\delta = -13\cdot2$ (upfield relative to external phosphoric acid). According to the literature[7], a negative shift of the phosphorus atom signal is characteristic of cyclic compounds of the type *IV* ($\delta = -27\cdot9$; ref.[7]). Thus, the observed negative chemical shift in the spectrum of *VIIb* indicates the presence of cyclic structure *VIIB* (Ar = 4-Cl—C_6H_4). For comparison, we also measured the ^{31}P NMR chemical shifts of the corresponding adduct with tributyl phosphine *II* (ref.[1]) (R = 4-Cl—C_6H_4, X = CHO), the methoxyacrolein *Vb* and the malonaldehyde *VIb* ($\delta = 34\cdot2$, $26\cdot9$, and $33\cdot4$, respectively).

In addition to signals of aromatic protons, the ^{1}H NMR spectrum (Table III) displays a doublet at $\delta = 3\cdot56$, corresponding to nine protons of three equivalent methoxy groups bonded to the phosphorus atom ($^3J(^1H, {}^{31}P) = 12\cdot5$ Hz). The equivalence of the methoxy groups was observed also in case of compound *IV* and is ascribed to pseudorotation[5]. The proton in the CH—P grouping gives rise

TABLE V

Coupling constants ^{13}C–^{1}H of compounds *Vb*, *VIb* and *VIIb* in deuteriochloroform

Coupling constant	Vb	VIb	VII
^1J(C-1, H-1)	174·1	—[a]	—[a]
^1J(C-3, H-3)	125·4	128·3	137·1
^1J(C-3, H-4)	171·7	—[a]	—[a]
^1J(C-6, H-6)	161·8	161·7	155·6
^1J(C-7, H-7)	169·3	166·6	165·8
^1J(OCH$_3$)	146·5	149·2	146·8
	146·5	148·9	146·8
	146·5	—	146·8
^2J(C-2, H-1)	25·4	17·2	18·6
^2J(C-2, H-3)	8·0	7·3	4·2
^2J(C-2, H-4)	8·0	17·2	18·6
^2J(C-5, H-3)	7·9	7·2	7·6
^2J(C-5, H-6)	7·9	7·2	7·6
^2J(C-6, H-7)	5·6	5·5	6·1
^2J(C-8, H-7)	5·2	4·5	3·6
^3J(C-1, H-3)	5·8	—[a]	—[a]
^3J(C-1, H-4)	5·8	—[a]	—[a]
^3J(C-3, H-1)	6·0	4·2	3·7
^3J(C-3, H-4)	3·6	4·2	3·7
^3J(C-3, H-5)	3·6	4·2	3·7
^3J(C-6, H-3)	6·8	5·5	6·1
^3J(OCH$_3$, H-4)	6·2	—	—

[a] Value not determined.

to a doublet at $\delta = 4\cdot18$ $(^2J(^1H, ^{31}P) = 19\cdot5$ Hz$)$. Instead of two signals due to the formyl and P—O—CH= protons, expected in the cyclic structure *VIIB*, we found only one broad two-proton signal at $\delta = 8\cdot65$. On cooling to 243 K, this signal split into two broad one-proton signals at $\delta = 9\cdot31$ (corresponding to the formyl group) and at $\delta = 8\cdot10$ (similar to the shift of the corresponding proton signals for substituted 2,3-dihydro-4*H*-pyrans $(\delta = 7\cdot4 - 8\cdot0)$). This behaviour can be explained by a rapid equilibrium between the cyclic and dipolar structure (Scheme 2). The
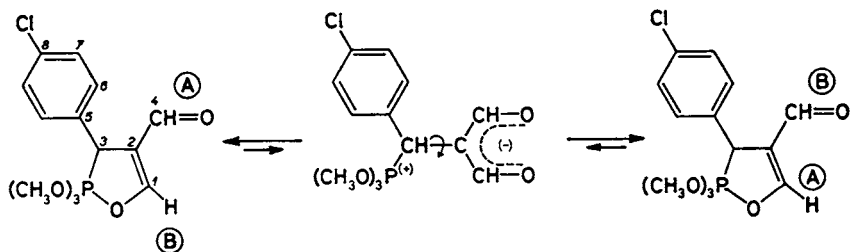

SCHEME 2

dipolar structure allows rotation about the C(2)—C(3) bond and thus an interchange of the atoms C-1 and C-4 (and the corresponding H(A) and H(B) protons) in the cyclic structure. If the equilibrium is shifted pronouncedly to the cyclic structure, the observed chemical shift should be approximately equal to the mean value of the —CH=O and =CH—O—P proton signals, which is indeed what we have found. Also the ^{31}P NMR shift corresponds to the cyclic structure. Finally, the concept of a rapid equilibrium between the cyclic and acyclic form with a marked preference of the former has been supported by ^{13}C NMR spectrum of *VIIb* (Tables IV and V). At 298 K, the so-called formyl atoms C-1 and C-4 give rise to a broad signal, $\delta = 175\cdot5$. The coupling constant $^1J(^{13}C, ^{31}P) = 158\cdot2$ Hz of the C-3 atom is close to that for compound *IV* $(^1J(^{13}C, ^{31}P) = 159\cdot5$ Hz$)$ whose ^{1}H and ^{13}C NMR spectra were measured for comparison (Tables III and IV). In the proton-coupled ^{13}C NMR spectrum, the C-2 signal appears at $\delta = 120\cdot6$ with three geminal coupling constants $^2J(^1H, ^{13}C)$ two of which amount to $18\cdot6$ Hz, and thus should belong to the rapidly interchanging formyl atoms H(A) and H(B), and the third one, $4\cdot2$ Hz, is due to the H-3 atom (Table V).

In malonaldehydes *VI* we can expect hydrogen bond formation, leading to six--membered (*VIA*) or seven-membered (*VIB*) ring species. The six-membered chelate ring occurs usually in β-dicarbonyl compounds, whereas seven-membered ring structures were observed in acylaminomalonaldehydes[9]. The NMR data indicate that in malonaldehydes *VI* the form *VIB* predominates. The two formyl protons of the

malonaldehyde system (Table III) are strongly non-equivalent in ^{1}H NMR spectra. Usually, these protons appear as a single two-proton signal because of rapid exchange of the enol proton between the carbonyl groups. The nonequivalence is also observed in the ^{13}C NMR spectrum (for *VIb* the corresponding chemical shifts are $\delta = 190.11$ and 169.54). Similarly, ^{1}H NMR spectra of compounds *V* show equivalent P—OCH$_3$ groups whereas in malonaldehydes *VI* the signals of methoxyl groups differ by $0.04-0.35$ ppm.

VI A   VI B
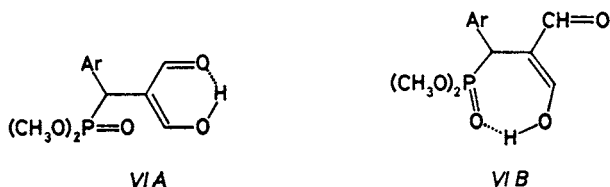
The P=O stretching vibrations in the IR spectra of malonaldehydes *VI* (1 246 to 1 249 cm^{-1}) (Table VI) are shifted compared with those of methoxyacroleins *V* (1 265 -- 1 272 cm^{-1}) (Table VII). The different chemical shifts of the phosphorus atom signals in the ^{31}P NMR spectrum ($\delta = 33.4$ for *VIb* and $\delta = 26.9$ for *Vb*) can also be ascribed to hydrogen bond formation.

TABLE VI

Infrared spectra of malonaldehydes *VI* (tetrachloromethane, cm^{-1})

Compound	$\nu(CH)^a$	$\nu(OH)$ (chelate)	$\nu(C=C-C=O)$	$\nu(P=O)$	$\nu(PO-CH_3)$
VIa	2 735 vw	2 600 — 3 100	1 682 w 1 618 m	1 247 m	1 061 w 1 043 m
VIb	2 735 m	2 600 — 3 100	1 681 m 1 620 s	1 246 s	1 045 vs 1 062 s, sh
VIc	2 734 m	2 500 — 3 100	1 680 s 1 620 vs	1 249 vs	1 042 vs 1 062 s
VId	2 731 m	2 600 — 3 100	1 679 s 1 618 vs	1 246 vs	1 045 vs 1 062 s
VIe	2 733 w	2 600 — 3 100	1 680 s 1 619 vs	1 246 s	1 045 vs 1 062 s, sh

^{a} In CH=O.

TABLE VII

Infrared spectra of methoxyacroleins V (tetrachloromethane, cm^{-1})

| Compound | CH=O | | $\nu(C=C)$ | $\nu(C-OCH_3; P=O)$ | $\nu(OCH_3)$ |
	$\nu(CH)$	$\nu(C=O)$			
Va	2 742 vw	1 682 m	1 648 s	1 267 s	1 039 s
		1 697 w, sh	1 633 m, sh		1 063 s
Vb	2 740 w	1 681 m	1 643 s	1 265 s	1 040 s
		1 697 m, sh	1 633 s, sh		1 061 s
Vc	2 735 vw	1 682 m, sh	1 648 s	1 253 vs	1 040 vs
		1 672 m, sh	1 634 s, sh	1 269 s, sh	1 064 s
		1 698 w, sh			
Vd	2 743 w	1 688 m	1 651 m	1 272 s	1 043 s
		1 999 w, sh			1 066 s
Ve	2 740 vw	1 684 w	1 652 m	1 271 m	1 064 m
					1 042 m

EXPERIMENTAL

Melting points were determined on a Kofler block. Analytical samples were dried over P_2O_5 at 25°C/25 Pa for 24 h. IR spectra were recorded on a Zeiss UR 20 spectrometer, ^1H NMR spectra were taken on Tesla BS 467 (60 MHz), Tesla BS 497 (100 MHz) and Varian XL-200 (200 MHz) instruments, ^{13}C and ^{31}P NMR spectra on Varian XL-200 (50·31 MHz and 80·96 MHz, respectively). UV spectra were measured on a Specord UV VIS spectrometer, mass spectra on an AEI MS-902 instrument.

Preparation of Methoxyacroleins V

The arylmethylenemalonaldehyde (2 mmol) was dissolved in benzene (4 ml; the 4-nitrophenyl and 2-thienyl derivatives did not dissolve completely) and trimethyl phosphite (2·24 ml) was added. The mixture warmed spontaneously and decolorized. After boiling under exclusion of moisture for 2 h, the mixture was cooled, the solvent evaporated *in vacuo* and the residue mixed with a small amount of ether and cooled. The separated product was filtered and washed with ether. The pure substance was obtained by two crystallizations from ethyl acetate–light petroleum.

Preparation of Malonaldehydes VI

Water (0·1 ml) and trimethyl phosphite (0·12 ml) were added to a solution of the arylmethylene-malonaldehyde (1 mmol) in tetrahydrofuran (3 ml). The reaction was almost instantaneous and was accompanied by strong temperature increase. The solvent was evaporated *in vacuo*, the residue mixed with a small amount of ether and set aside at 0°C overnight. The product was filtered and washed with small amount of ether.

Isolation of the primary product VIIb: Trimethyl phosphite (0·12 ml) was added to a solution of 4-chlorophenylmethylenemalonaldehyde (0·195 g; 1 mmol) in benzene (1 ml). The solution warmed spontaneously and decolorized. After cooling, light petroleum was added to turbidity (about 5 ml) and the solution was cooled with ice. The product was collected on filter, washed with light petroleum under exclusion of air and dried *in vacuo* at 0°C. Yield 0·23 g (72%) of VIIb, m.p. 45−50°C.

Hydrolysis of VIIb: Trimethyl phosphite (0·12 ml; 1 mmol) was added to a solution of 4-chlorophenylmethylenemalonaldehyde (1 mmol) in tetrahydrofuran (3 ml). The solution warmed spontaneously and the yellow colour disappeared. After cooling, water (0·5 ml) was added and a strong spontaneous warming occured again. The solvent was evaporated and the remaining solid, m.p. 110−118°C, was identified as *VIb* on the basis of spectral evidence. Under the same conditions (aqueous tetrahydrofuran) the methoxyacrolein *Vb* is stable; only after acidification (*e.g.* with a drop of acetic or perchloric acid) it was rapidly hydrolyzed (monitored by thin-layer chromatography on Silufol in chloroform–acetone 1 : 1).

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