

Anodic Oxidation of Organophosphorus Compounds. Part 2.¹ Formation of Dialkyl Arylphosphonates *via* Arylation of Trialkyl Phosphites

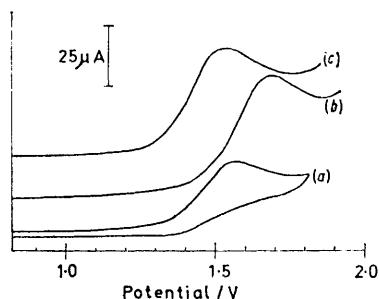
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Anodic oxidation of trialkyl phosphites (1) has been investigated by cyclic voltammetry and controlled-potential electrolysis at a glassy-carbon electrode in acetonitrile. On electrolysis of (1) in the presence of an excess of various substituted benzenes, formation of trialkoxyarylphosphonium ion was recognized. The reaction sequence is suggested to be one-electron oxidation of (1), electrophilic attack of the resulting cation radical on the aromatic hydrocarbon, and a further one-electron transfer and loss of a proton. The phosphonium ion was converted into the corresponding dialkyl arylphosphonate on treatment with sodium iodide.

PREVIOUSLY we have reported the anodic alkylation of triphenylphosphine.¹ Since only limited attention has been paid to the anodic oxidation of organophosphorus compounds, it seemed of interest to explore other possibilities of anodic substitution reactions at the phosphorus atom.

Various methods have been reported for the preparation of arylphosphonates,² but these do not include the direct reaction of aromatic hydrocarbons with trialkyl phosphites. Anodic oxidation of organic compound usually gives strong electrophiles such as cation radicals and/or cations, which may react even with a very weak nucleophile present in the reaction system. In fact triphenylphosphine cation radical was found to react

peak current (i_p) of the anodic wave increased without exception, but the peak potential (E_p) varied randomly (*cf.* the Figure). The i_p and the E_p values are summarized in Table 1. The substituted benzenes showed no voltammetric peak under the experimental conditions.



Cyclic voltammograms of (EtO)₃P (5mM) (a) in acetonitrile, (b) in acetonitrile containing 1% benzene, and (c) in acetonitrile containing 1% t-butylbenzene; 0.1M-NaClO₄, 0.05 V s⁻¹

with benzene to form tetraphenylphosphonium ion.³ Thus, if arylation of a trialkyl phosphite is effected electrochemically, the resulting phosphonium ion will be easily converted into the corresponding arylphosphonate. We report here the results of oxidation of trialkylphosphites in acetonitrile at a glassy-carbon electrode in the presence of various substituted benzenes.

RESULTS AND DISCUSSION

Trialkyl phosphites (RO)₃P (1; a, R = Me; b, R = Et; c, R = Pr¹) showed a single anodic peak on cyclic voltammetry in acetonitrile containing 0.1M sodium perchlorate. No cathodic peak was observed down to -0.1 V in the reverse scan. A typical voltammogram is shown in the Figure. All potentials were measured against an aqueous saturated calomel electrode (s.c.e.). In the presence of an excess of substituted benzenes the

TABLE I

Results of cyclic voltammetry of (1) in acetonitrile^a

Compound	Additives ^b	E_p /V ^c	i_p /μA
(EtO) ₃ P	None	1.57	26.3
	Benzene	1.68	47.5
	Toluene	1.60	48.1
	Ethylbenzene	1.65	46.9
	Cumene	1.65	47.5
	t-Butylbenzene	1.53	45.6
(MeO) ₃ P	<i>o</i> -Xylene	1.60	50.0
	None	1.64	35.0
	Benzene	1.68	47.5
	Toluene	1.68	46.3
	Ethylbenzene	1.60	46.3
	Cumene	1.65	45.6
(Pr ¹ O) ₃ P	t-Butylbenzene	1.60	45.6
	<i>o</i> -Xylene	1.60	48.3
	None	1.45	30.1
	Benzene	1.68	46.9
	Toluene	1.58	49.1
	Ethylbenzene	1.56	49.1

^a 0.1M-NaClO₄; concentration of substrate, 5 mM; voltage scan rate, 50 mV s⁻¹; geometric electrode area, 0.071 cm².

^b Concentration of benzenes, 1%. ^c V vs. the s.c.e.

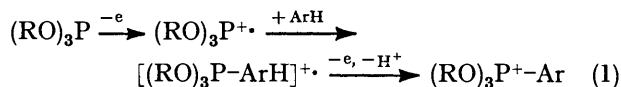
Electrolysis of (1b) in acetonitrile at 1.5 V gave an unexpectedly low coulometric n -value ($n = 0.3-0.4$). Diethyl hydrogenphosphite was the only product isolated successfully from the reaction mixture by column chromatography. It has been reported that trialkyl phosphite is readily hydrolysed to give dialkyl hydrogenphosphite, and that the reaction is catalysed by a trace amount of acid and/or dialkyl hydrogenphosphite itself.⁴ The acetonitrile used may be contaminated with a considerable amount of water as was observed in the anodic oxidation of triphenylphosphine.¹ If the water brings about a similar anodic substitution reaction to that in the case of triphenylphosphine,¹ hydrogen ions will be liberated, which will then accelerate the hydrolysis of the substrate. The effects of water on the cyclic voltammetry of (1b) were thus examined. The i_p value of the anodic peak of (1b) (5mM) in acetonitrile increased on addition of water when the concentration of water was less than 3%, indicating the

possibility of the anodic substitution reaction mentioned above. With further increase in the amount of water, however, the i_p value decreased, and in the presence of 10% water the anodic peak was no longer observed even when the voltammetric measurement was carried out immediately after the solution was prepared. Formation of diethyl hydrogenphosphite was recognized in the solution (see Experimental section). The latter results support the view that the hydrolysis of (1b) proceeds easily without acid catalysis. Thus the main reaction in the electrolysis of (1) in acetonitrile can be regarded as an electrolytically promoted hydrolysis of the substrate, and seems to have little synthetic value. The reaction was not studied further.

Electrolysis of (1b) in acetonitrile containing excess of benzene at 1.7 V gave a coulometric n -value of *ca.* 1, and the formation of $(\text{EtO})_3\text{P}^+-\text{Ph}$ (see below) and

On electrolysis in the presence of alkylbenzenes, positional isomers of dialkyl arylphosphonates were formed (see Table 3). In the case of toluene, ethylbenzene, or *o*-xylene, the isomers were characterized by ^1H n.m.r. spectra.⁷ The signals due to the methyl or methylene group on the phenyl ring *ortho* to the phosphono-group are split into doublets by coupling with the phosphorus atom, whereas no such splitting is observed for those *meta* or *para* to the phosphono-group.

The following scheme can be suggested for the anodic arylation of (1). The increase in the voltammetric peak



height in the presence of substituted benzenes (Figure) and the formation of *ortho*- and *para*-isomers are com-

TABLE 2

Results of controlled-potential electrolysis of (1) in acetonitrile in the presence of substituted benzenes^a

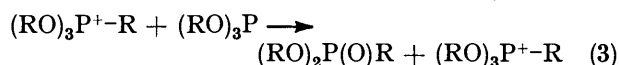
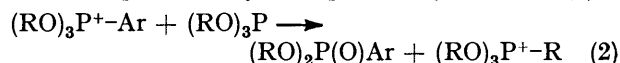
Compound	Amount	Additives mmol	Amount of K_2CO_3 / g^b	Applied potential ^c	n -value	Yield (%) of $(\text{RO})_2\text{P}(\text{O})\text{Ar}^d$	Other products identified (%) ^d
$(\text{EtO})_3\text{P}$	(10)	Benzene (50)	None	1.70	0.96	34	$(\text{EtO})_3\text{PH}^+$ (37) ^e
	(10)	Benzene (50)	3	1.70	1.56	54	
	(5)	Benzene (25)	3	1.70	1.60	59	
	(5)	PhMe (25)	3	1.60	1.69	64 ^f	
	(10) ^g	PhEt (50)	5	1.60	1.69	53 ^f	
	(5)	PhPr ^l (25)	3	1.55	1.81	50 ^f	
	(5)	PhBu ^t (25)	3	1.60	1.94	66 ^f	
	(5)	$\text{C}_6\text{H}_4\text{Me}_2$ - <i>o</i> (25)	3	1.55	1.80	53 ^f	
$(\text{MeO})_3\text{P}$	(11)	Benzene (50)	5	1.70	0.48	16	$(\text{MeO})_2\text{P}(\text{O})\text{Me}$ (48)
	(8)	PhMe (50)	3	1.60	0.46	14 ^f	$(\text{MeO})_2\text{P}(\text{O})\text{Me}$ (45)
	(12)	PhEt (50)	5	1.55	0.44	14 ^f	$(\text{MeO})_2\text{P}(\text{O})\text{Me}$ (46)
$(\text{Pr}^i\text{O})_3\text{P}$	(11) ^g	Benzene (50)	5	1.70	1.10	41	$(\text{Pr}^i\text{O})_2\text{P}(\text{O})\text{Pr}^i$ (trace)
	(6.5)	PhMe (25)	3	1.50	0.86	38 ^f	$(\text{Pr}^i\text{O})_2\text{P}(\text{O})\text{Pr}^i$ (34)
	(12)	PhEt (50)	5	1.55	0.85	36 ^f	$(\text{Pr}^i\text{O})_2\text{P}(\text{O})\text{Pr}^i$ (35)

^a The volume of anolyte was 40 ml unless otherwise noted. Sodium perchlorate (0.2M) was used as the supporting electrolyte. Electrolysis was carried out under stream of dry nitrogen at room temperature. ^b Suspended in the anode compartment. ^c V *vs.* the s.c.e. ^d Based on the isolated product after distillation. ^e See Experimental section. ^f Mixture of positional isomers (*cf.* Table 3). ^g The volume of anolyte was 100 ml.

$(\text{EtO})_3\text{PH}^+$ was suggested. When the electrolysis was carried out in the presence of suspended potassium carbonate, the n -value was *ca.* 1.6 and a pale yellow oil was obtained. I.r. and ^1H n.m.r. spectra indicated that the oil was a mixture of $[(\text{EtO})_3\text{P}^+-\text{Ph}][\text{ClO}_4^-]$ and $(\text{EtO})_2\text{P}(\text{O})\text{Ph}$. Phosphonium salts having at least one alkoxy-group are usually unstable, although examples of their isolation have been reported.^{5,6} Thus the phosphonate ester is considered to be formed from the phosphonium salt by hydrolysis, for which water contaminating the acetonitrile and/or moisture absorbed during work-up may be responsible. On treatment with sodium iodide in dry acetone, the phosphonium salt in the mixture was converted to the phosphonate. Typical results of controlled potential electrolysis are summarized in Table 2. Except for the example described above, no attempt was made to detect the formation of phosphonium salts, and the products from electrolysis were isolated as arylphosphonates. Details of the procedures and identification of the products are described in the Experimental section.

patible with an electrophilic aromatic substitution reaction taking place between the two electron transfers. In the absence of suspended potassium carbonate, half of the starting phosphite will be protonated, and the coulometric n -value will be unity.

In the electrolysis of (1a) and (1c), $(\text{MeO})_2\text{P}(\text{O})\text{Me}$ and $(\text{Pr}^i\text{O})_2\text{P}(\text{O})\text{Pr}^i$ were formed, respectively, in addition to the corresponding aryl phosphates. The formation of these compounds may be explained by reactions (2) and



(3). With (1a) reaction (3) was found to be very fast.⁵ Since these reactions consume the starting phosphite without electrolysis, the observed n -value is smaller than that expected (see Table 2). It is not clear why participation of reactions (2) and (3) is not significant in the case of (1b).

The electrochemical modification of the Michaelis-

TABLE 3

Isomer ratio and ^1H n.m.r. data of $(\text{RO})_2\text{P}(\text{O})\text{Ar}$ obtained on controlled potential electrolysis

Compound	Isomer ratio (<i>ortho</i> : <i>para</i>)	^1H N.m.r. $^a/\delta$
R = Et		
Ar = MeC_6H_4	3 : 5	1.32 (t, $J = 7, 6$ Hz); 2.38 (s) and 2.57 (d, $J = 2$) (total 3 H); ^b 4.12 (quintet, $J_{\text{HH}} = J_{\text{PH}} = 7, 4$ Hz); 7.12–8.15 (m, 4 H)
Ar = EtC_6H_4	1 : 5	1.11–1.77 (m, 9 H); 2.68 (q, $J = 7$) and 3.00 (d of q, $J_{\text{HH}} = 7, J_{\text{PH}} = 1.5$) (total 2 H); ^b 4.12 (quintet, $J_{\text{HH}} = J_{\text{PH}} = 7, 4$ Hz); 7.13–8.11 (m, 4 H)
Ar = $\text{Pr}^i\text{C}_6\text{H}_4$	<i>c</i>	1.13–1.62 (m, 12 H); 2.67–3.10 (m, 1 H); 4.10 (quintet, $J_{\text{HH}} = J_{\text{PH}} = 7, 4$ Hz); 7.13–7.98 (m, 4 H)
Ar = $\text{Bu}^t\text{C}_6\text{H}_4$	<i>c</i>	1.21–1.73 (m, 15 H); 4.13 (quintet, $J_{\text{HH}} = J_{\text{PH}} = 7, 4$ Hz); 7.33–8.02 (m, 4 H)
Ar = $\text{Me}_2\text{C}_6\text{H}_3$	2 : 9 ^d	1.31 (t, $J = 7, 6$ Hz); 2.26 (s) and 2.48 (d, $J = 2$) (total 6 H); ^b 4.18 (quintet, $J_{\text{HH}} = J_{\text{PH}} = 7, 4$ Hz); 7.12–7.95 (m, 3 H)
R = Me		
Ar = MeC_6H_4	3 : 7	2.37 (s) and 2.53 (d, $J = 2$) (total 3 H); ^b 3.63 (d, $J = 11, 6$ Hz); 6.98–8.07 (m, 4 H)
Ar = EtC_6H_4	1 : 5	1.27 (t, $J = 7, 3$ Hz); 2.69 (q, $J = 7$) and 2.98 (d of q, $J_{\text{HH}} = 7, J_{\text{PH}} = 1.5$) (total 2 H); ^b 3.75 (d, $J = 11, 6$ Hz); 7.03–8.03 (m, 4 H)
R = Pr^i		
Ar = MeC_6H_4	1 : 2	1.29 (t, $J_{\text{HH}} = J_{\text{PH}} = 6, 12$ Hz); 2.38 (s) and 2.56 (d, $J = 2$) (total 3 H); ^b 4.32–4.96 (m, 2 H); 7.05–8.15 (m, 4 H)
Ar = EtC_6H_4	1 : 7	1.10–1.52 (m, 15 H); 2.67 (q, $J = 7$) and 3.00 (d of q, $J_{\text{HH}} = 7, J_{\text{PH}} = 1.5$) (total 2 H); ^b 4.35–4.95 (m, 2 H); 7.03–7.95 (m, 4 H)

^a The ^1H n.m.r. spectra (60 MHz) were recorded in CDCl_3 with SiMe_4 as internal standard, J values in Hz. ^b These signals were used to obtain the isomer ratio. ^c The isomer ratio could not be obtained. ^d 2,3-Dimethyl : 3,4-dimethyl.

Arbuzov reaction described in this paper suffers inherently from the defect of isomer formation. However, the use of simple starting materials makes the procedure synthetically viable for the preparation of phenylphosphonates.

EXPERIMENTAL

Materials.—Trialkyl phosphites were purified by distillation. Benzene and alkylbenzenes were purified by conventional methods. Sodium iodide was dried in an oven at 120 °C for 8 h. Sodium perchlorate⁸ and acetonitrile¹ were purified as described previously.

Apparatus.—Cyclic voltammetry and controlled-potential electrolysis were carried out as described previously.⁹ All voltammetric measurements were carried out at 25 ± 0.05 °C. I.r. and ^1H n.m.r. spectra were obtained using Hitachi EPI-2 and R-20A spectrometers, respectively.

Controlled-potential Electrolyses.—Typical examples of the procedure are described.

(a) **Electrolysis in acetonitrile containing excess of benzene with suspended potassium carbonate.** Compound (1b) (830 mg, 5 mmol) was subjected to electrolysis at 1.7 V in acetonitrile (40 ml) containing 0.2M- NaClO_4 and 25 mmol of benzene with K_2CO_3 (3 g) suspended in the anode compartment until the current became <2% of the initial value (*ca.* 10 h). Before electrolysis dry nitrogen was bubbled through the anolyte for 5 min, and during the course of electrolysis the anode compartment was kept under an atmosphere of N_2 . From the current-time curve 772 C, which corresponded to $n = 1.60$, was found to be consumed. After removal of the potassium carbonate by filtration, the anolyte was evaporated to dryness under reduced pressure and the residue was extracted with chloroform (3 × 20 ml). Evaporation of the chloroform under reduced pressure gave a pale yellow oil, which was suggested to be a mixture of $[(\text{EtO})_3\text{P}^+-\text{Ph}][\text{ClO}_4^-]$ and $(\text{EtO})_2\text{P}(\text{O})\text{Ph}$ as follows. I.r. spectra of the oil showed a characteristic absorption around 1100 cm^{-1} due to the perchlorate anion. ^1H N.m.r. spectra (CDCl_3 ; SiMe_4 internal reference) showed two triplets at δ 1.31 (J 7 Hz) and 1.57 (J 6 Hz), two quintet-like multiplets at δ 4.11 (J 7 Hz) and 4.65 (J 6 Hz), and signals due to phenyl protons between δ 7.2 and 8.2. The signals at δ 1.31 and 4.11 coincided with those of diethyl phenylphosphonate under the same conditions, for which the signals of the phenyl protons were observed at δ 7.2–8.1. The signals at δ 1.57 and 4.65 can be compared with those of the ethoxy-protons of $[(\text{EtO})_3\text{P}^+-\text{Me}][\text{OSO}_2\text{CF}_3^-]$ at δ 1.45 (t, J 6 Hz) and 4.4 (m, J 6 Hz),⁵ and can be assigned to the corresponding ethoxy-protons of triethoxyphenylphosphonium perchlorate. The signals due to the phenyl protons of the latter phosphonium ion were mixed with those of diethyl phenylphosphonate in the mixture.

In a 100-ml round-bottomed flask equipped with a reflux condenser with a drying tube were placed the oil described above, dry acetone (100 ml), and dry sodium iodide (0.9 g). The mixture was refluxed for 6 h. After being cooled to room temperature, acetone was removed under reduced pressure, and water (100 ml) was added to the residue. The resulting mixture was extracted with ether (3 × 30 ml) and then chloroform (2 × 20 ml). The organic layer, after being dried with anhydrous MgSO_4 , was evaporated under reduced pressure with a nitrogen stream at room temperature. Distillation of the residue gave pale yellow oil (632 mg; bath temperature 160 °C at 0.1 mmHg), which was identified as diethyl phenylphosphonate by elemental analysis, and i.r. and ^1H n.m.r. spectra. Other dialkyl arylphosphonates were obtained and characterized similarly. In the case of dialkyl arylphosphonates derived from toluene, ethylbenzene, and *o*-xylene, the isomer ratio (Table 3) was estimated from the area of ^1H n.m.r. signals due to the corresponding methyl or methylene protons on the phenyl ring, by assuming that only the *ortho*- and *para*-isomers were formed.

Dimethyl methylphosphonate and di-isopropyl isopropylphosphonate obtained in the electrolysis of (1a) and (1c), respectively, were separated from the corresponding arylphosphonates by fractional distillation as colourless oils (b.p. 67 °C at 12 mmHg and 107 °C at 15 mmHg, respectively), after the solutions from electrolysis had been worked-up in a similar manner to that described above.

(b) **Electrolysis in acetonitrile containing excess of benzene**

without potassium carbonate. Compound (1b) (1 660 mg) was subjected to electrolysis similarly at 1.7 V in acetonitrile (40 ml) containing 50 mmol of benzene. A coulometric n -value of 0.91 was obtained. The solution from electrolysis showed no voltammetric peak due to (1b). When passed through a short column of potassium carbonate, however, the solution showed an anodic peak at 1.69 V, which coincided with that of (1b) in the presence of excess of benzene, indicating that part of the starting phosphite had been protonated on electrolysis. From the peak height the recovery of (1b) was found to be 37%. In another run [(1b) 1 660 mg; $n = 0.96$], the solution from electrolysis was evaporated to dryness under reduced pressure, and the residue was worked-up as described in (a) to give diethyl phenylphosphonate (725 mg).

(c) *Electrolysis of (1b) in acetonitrile.* Compound (1b) (431 mg) was subjected to electrolysis at 1.5 V in acetonitrile. A coulometric n -value of 0.3 was obtained. The solution from electrolysis, which showed no voltammetric peak due to (1b), was evaporated to dryness under reduced pressure, and the residue was subjected to column chromatography on neutral alumina using chloroform as eluant. From the first effluent diethyl hydrogenphosphite was obtained (small amount), which was identified by comparing the i.r. and ^1H n.m.r. spectra with those of authentic sample.

Identification of Diethyl Hydrogenphosphite in Acetonitrile containing 10% Water.—Compound (1b) (831 mg) was

* Since diethyl hydrogenphosphite is soluble in water, it was not extracted efficiently with chloroform.

dissolved in acetonitrile (40 ml) containing 0.1M- NaClO_4 and 10% water. The solution showed no voltammetric peak due to (1b). Water (25 ml) was added to the solution, and the mixture was extracted quickly with chloroform (3×50 ml). After being dried with anhydrous MgSO_4 , the chloroform layer was evaporated to give diethyl hydrogenphosphite.*

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REFERENCES

- ¹ Part I, H. Ohmori, S. Nakai, and M. Masui, *J.C.S. Perkin I*, 1978, 1333.
- ² K. H. Worms and M. Schmidt-Dunker, in 'Organic Phosphorus Compounds,' eds. G. M. Kosolapoff and L. Maier, Wiley, New York and London, 1976, vol. 7, ch. 18, and references therein.
- ³ G. Schiavon, S. Zecchin, G. Giannicogoni, and G. Bontempelli, *J. Electroanalyt. Chem.*, 1973, **43**, 425.
- ⁴ A. E. Arbuzov, *J. Russ. Phys. Chem. Soc.*, 1914, **46**, 291 (*Chem. Abs.*, 1914, **8**, 2551); M. G. Lmaev, *Zhur. obshchei. Khim.*, 1961, **31**, 1762 (*Chem. Abs.*, 1961, **55**, 24,531f).
- ⁵ K. S. Colle and E. S. Lewis, *J. Org. Chem.*, 1978, **43**, 571.
- ⁶ P. Beck, in 'Organic Phosphorus Compounds,' eds. G. M. Kosolapoff and L. Maier, Wiley, New York and London, 1972, vol. 2, ch. 4.
- ⁷ C. E. Griffin, R. B. Davison, and M. Gordon, *Tetrahedron*, 1966, **22**, 561.
- ⁸ M. Masui and H. Ohmori, *J.C.S. Perkin II*, 1972, 1882.
- ⁹ H. Sayo and M. Masui, *J.C.S. Perkin II*, 1973, 1640.