Acta Chemica Scandinavica B 35 (1981) 13–18

Effect of *Para* Substituents on ^{31}P Chemical Shifts of Alkyl Phenyl Phenylphosphonates

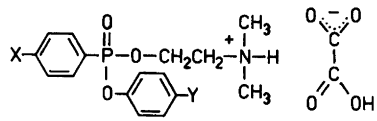
P. ANTTI MANNINEN

Department of Chemistry, University of Helsinki, SF-00100 Helsinki 10, Finland

Fifteen derivatives of oxalates of 2-(*N*,*N*-dimethylammonio)ethyl phenyl phenylphosphonates were prepared and ^{31}P chemical shifts were measured in 50 % ethanol and in dimethylsulfoxide-d_6. The phenyl and phenoxy groups were both substituted at the *para*-position. The substituents of the phenyl group had a similar, distinct effect on the chemical shift in both solvents. The effect of the substituents of the phenoxy group was 5–6 times smaller and clearly depended on the medium. The chemical shifts have been correlated with the parameter σ_p° and its components σ_I and σ_R°, and the dual-substituent parameter approach has been applied.

Linear correlations are not usually found between ^{31}P chemical shifts and the general substituent constants. For example, ^{31}P chemical shifts of phosphonates and phosphonium salts do not correlate linearly with Taft σ^* parameters,[1] nor do the chemical shifts of triarylphosphines with Hammett σ_p parameters.[2] Because linear correlations for phosphorus compounds are lacking and, in particular, substituent additivity does not hold well, other parameters have been developed for the evaluation of chemical shifts from substituent properties. Group contributions presented by Grim[2,3] and recently improved by Payne and Stephan[4] have been found suitable for the prediction of ^{31}P chemical shifts of phosphines. Nevertheless there is no simple relationship between these group contributions and chemical reactivity, and the applicability of these parameters to other phosphorus compounds is doubtful.

There are so many substituent parameters reported in the literature that it would seem desirable to try and use parameters already known rather than to define and determine new ones. Accordingly, in the correlations of this work the substituent parameters σ_p°, σ_I and σ°_R have been amployed. The aromatic system has been chosen for study because the changing of substituents at the *para* position causes only minimal variations in the bond angles of phosphorus and the effect on the chemical shift can be neglected. The compounds studied were disubstituted derivatives of oxalates of 2-(*N*,*N*-dimethylammonio)ethyl phenyl phenylphosphonates, shown in Scheme 1.



X = CH_3, CH_3O, H or Br and
Y = CH_3, CH_3O, H or Br except X=Y= Br

Scheme 1.

RESULTS AND DISCUSSION

The ammonium group may ionize: $Ar(ArO)P(O)OCH_2CH_2NMe_2H^+ \rightleftharpoons Ar(ArO)P(O)OCH_2CH_2NMe_2 + H^+$ and the reaction can have an effect on chemical shift changes. Therefore the non-ionizable compound 2-(*N*,*N*,*N*-trimethylammonio) ethyl phenyl phenylphosphonate iodide was prepared and the dependence of ^{31}P chemical shift of this compound and the oxalate *6* (see Table 1) on concentration in 50 % ethanol (see experimental section) was studied. The similar dependence for the two compounds (Fig. 1) indicates that the ionization of the ammonium group is not an important factor in the chemical shift differences caused by substituents. In addition, the acidity of the medium

0302-4369/81/010013-06$02.50

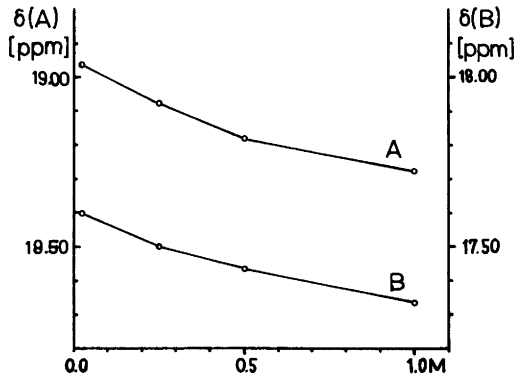


Fig. 1. Dependence of ^{31}P chemical shifts of oxalate of 2-(*N*,*N*-dimethylammonio)ethyl 4-methoxyphenyl 4-methoxyphenylphosphonate (A) and iodide of 2-*N*,*N*,*N*-trimethylammonio)ethyl phenyl phenyl phosphonate (B) on concentration in 50 % ethanol.

has practically no effect on the chemical shifts of either compound when pH < 4. At higher pH values the ammonium group will be deprotonated, and the chemical shift will decrease sharply.

The chemical shifts were measured at pH 3.3 ± 0.1 in 50 % ethanol and dimethylsulfoxide-d_6 and are presented in Table 1. The Table shows that in both solvents the substituent X has about five to six times greater effect on the chemical shift than the substituent Y. A change of X has only a negligible effect on the substituent properties of Y and in reverse Y does not influence properties of X, as revealed in Table 2. This shows the ^{31}P chemical shift differences from the unsubstituted (H-substituted) derivative and the mean values of these. For instance, it can be seen that the contribution of $X = CH_3$ in chemical shift measured in 50 % ethanol is always about +0.763 ppm. Standard deviations of the mean values (in parentheses) are about the same order of magnitude as the error of the measurements. Actually it seems clear that all the information on substituent effects is contained in one series of substituents for the phenyl group (constant Y) and in the other one for the phenoxy group (constantX). The mean values given have, therefore, been used in the correlations below.

The substituent constants are shown in Table 3. The refined values presented recently by Bromilow *et al.*,[5] which are suitable for non-polar solvents, are not used here since they differ little from the older values and the present media are polar.

A satisfactory linear correlation was found between ^{31}P chemical shifts and σ_p° parameter of substituent X in both solvents (Fig. 2a). This parameter is not suitable, however, for correlating sub-

Table 1. ^{31}P chemical shifts of oxalates of 2-(*N*,*N*-dimethylammonio)ethyl phenyl phenylphosphonates (Scheme 1) measured in 50 % ethanol and in dimethylsulfoxide-d_6 and melting points of same compounds. The last column shows boiling points of the respective phenyl phenylphosphonochloridates (pressure/Pa given in parentheses).

	X	Y	δ_{XY}[a] 50 % EtOH	δ_{XY} DMSO-d_6	M.p. of oxalate/°C	B.p. of Ph-PO(OPh)Cl/°C(Pa)
1	CH_3	CH_3	18.481	16.318	118–119	174–175(53)
2		CH_3O	18.775	16.566	114–115	190–192(27)
3		H	18.420	16.291	132–133	160–165(40)
4		Br	18.593	16.559	130–131	200–205(80)
5	CH_3O	CH_3	18.748	16.657	141–142	208–210(67)
6		CH_3O	19.042	16.906	142–143	234–237(80)
7		H	18.673	16.627	126–127	195–198(53)
8		Br	18.862	16.898	118–119	216–220(80)
9	H	CH_3	17.716	15.655	137–138	165–168(53)
10		CH_3O	18.013	15.903	129–131	179–182(40)
11		H	17.659	15.625	126–128	148–152(40)
12		Br	17.829	15.881	132–133	179–182(40)
13	Br	CH_3	16.578	14.645	129–131	181–185(27)
14		CH_3O	16.876	14.896	123–124	201–205(27)
15		H	16.529	14.622	146–147	186–189(67)

[a] Chemical shifts (ppm) are positive when downfield from reference.

Table 2. ^{31}P chemical shift differences and mean values of these calculated from Table 1 with the respective unsubstituted (H-substituted) compound as reference. Standard deviations are in parentheses. The zero values of the reference compounds are not shown.

X	Y	$\delta_{XY}-\delta_{HY}$ 50 % EtOH	DMSO-d_6	X	Y	$\delta_{XY}-\delta_{XH}$ 50 % EtOH	DMSO-d_6
CH_3	CH_3	0.765	0.663	CH_3	CH_3	0.061	0.027
	CH_3O	0.762	0.663	CH_3O		0.075	0.030
	H	0.761	0.666	H		0.057	0.030
	Br	0.764	0.678	Br		0.049	0.023
Mean value		0.763(2)	0.667(8)			0.061(11)	0.027(4)
CH_3O	CH_3	1.032	1.002	CH_3	CH_3O	0.355	0.275
	CH_3O	1.029	1.003	CH_3O		0.369	0.279
	H	1.014	1.002	H		0.354	0.278
	Br	1.033	1.017	Br		0.347	0.274
Mean value		1.027(9)	1.006(7)			0.356(10)	0.276(2)
Br	CH_3	−1.138	−1.010	CH_3	Br	0.173	0.268
	CH_3O	−1.137	−1.007	CH_3O		0.189	0.271
	H	−1.130	−1.003	H		0.170	0.256
Mean value		−1.135(5)	−1.006(4)			0.177(10)	0.265(8)

stituent effects of Y. Therefore σ_I and σ_R° parameters and linear combinations of these were tested instead and the effect of Y was found to be acceptably described by σ_R° for the chemical shifts measured in 50 % ethanol and by $\sigma_I-\sigma_R^\circ$ for those measured in dimethylsulfoxide-d_6 (Fig. 2b).

To get a more linear fitting than those shown in Fig. 2, it is tempting to determine the coefficients of σ_I and σ_R° (which were in the previous presentation arbitrarily chosen as 0, −1 or +1) by a multilinear regression method despite the small number of independent observations. The regression equations are eqns. (1) and (2), where ρ_X, ρ_Y, $(\rho_X\lambda_X)$ and $(\rho_Y\lambda_Y)$

$$\delta_{XY}-\delta_{HY}=\delta'+\rho_X\sigma_{IX}+(\rho_X\lambda_X)\sigma_{RX}^\circ$$
$$=\delta'+\rho_X(\sigma_{IX}+\lambda_X\sigma_{RX}^\circ) \quad (1)$$

$$\delta_{XY}-\delta_{XH}=\delta''+\rho_Y\sigma_{IY}+(\rho_Y\lambda_Y)\sigma_{RY}^\circ$$
$$=\delta''+\rho_Y(\sigma_{IY}+\lambda_Y\sigma_{RY}^\circ) \quad (2)$$

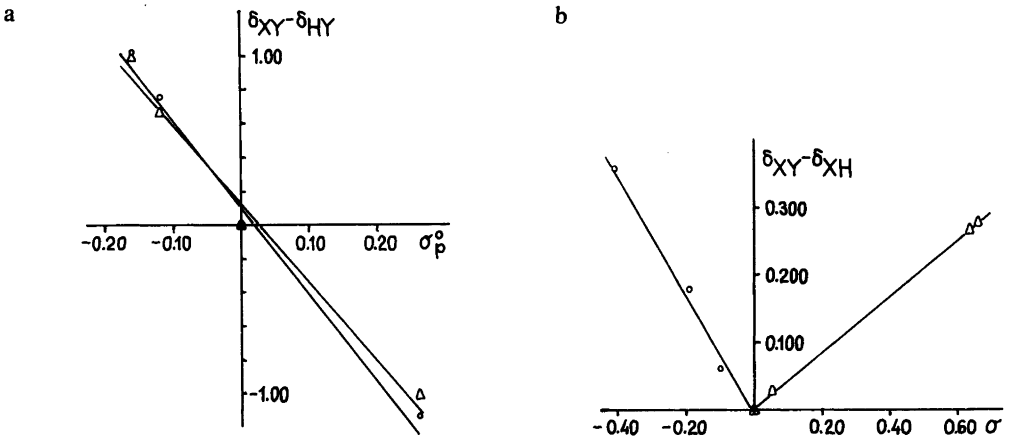


Fig. 2. Dependence of mean values of relative ^{31}P chemical shifts (from Table 2); on σ_p° parameter of a, the substituent X in 50 % ethanol (o) and in dimethylsulfoxide-d_6(Δ); b, on σ_R° parameter of the substituent Y in 50 % ethanol (o) and on $\sigma_I-\sigma_R^\circ$ in dimethylsulfoxide-d_6 (Δ).

Table 3. Substituent constants from Ref. 7 and linear combinations of these calculated from experimental data determined in 50 % ethanol and dimethylsulfoxide-d_6. Values λ are taken from Table 4.

	CH_3	CH_3O	H	Br
σ_p°	−0.12	−0.16	0	+0.26
σ_I	−0.05	+0.25	0	+0.45
σ_R°	−0.10	−0.41	0	−0.19
50 % EtOH				
$\sigma_{IX}+\lambda_X\sigma_{RX}^\circ$	−0.165	−0.222	0.000	+0.231
$\sigma_{IY}+\lambda_Y\sigma_{RY}^\circ$	+1.15	+5.17	0.00	+2.73
DMSO-d_6				
$\sigma_{IX}+\lambda_X\sigma_{RX}^\circ$	−0.169	−0.238	0.000	+0.224
$\sigma_{IY}+\lambda_Y\sigma_{RY}^\circ$	+0.050	+0.660	0.000	+0.640

are coefficients to be calculated and δ' and δ'' the deviations from zero. The use of only four points (mean values) in regressions instead of fifteen measurements gives more realistic standard deviations of coefficients. The multiple regression coefficient will be, in any case, near 1 because there are two independent variables and only four observations.

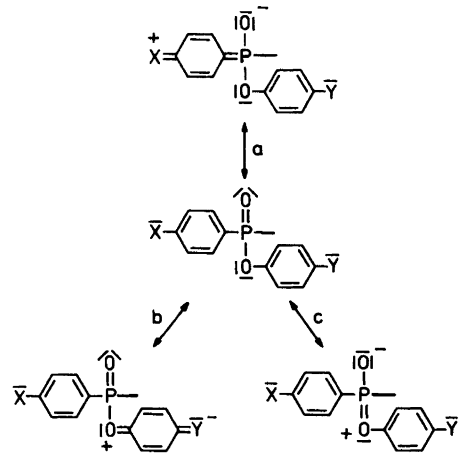
Actually, eqns. (1) and (2) are in the form used in the dual-substituent parameter approach, which has been employed to find out new or to refine known σ_I and σ_R° parameters of substituents of the benzene ring.[5,6] In this approach the relative chemical shifts of *meta* and *para* carbon atoms of monosubstituted benzene derivatives are expressed as in eqn. (3), where δ_X is the chemical shift of the

$$\delta_X-\delta_H=a\sigma_I+b\sigma_R^\circ \qquad (3)$$

meta or para carbon atom and a and b are the proportionally factors. The term $a\sigma_I$ is attributed to the effect of substituent-induced polarization of ring π electrons and the term $b\sigma_R^\circ$ to the effect of π electron delocalization of the benzene ring.

When this approach is applied to chemical shift changes of a phosphorus atom joined directly or through an oxygen atom to the *para* position of the benzene ring, the electrons could be regarded as delocalized over the benzene ring and phosphoryl group (Scheme 2, a). The oxygen atom of the phenoxy group takes part in the resonance by donating free electron pairs to both the phosphorus atom and the benzene ring (Scheme 2, b and c).

The coefficients ρ_X and $(\rho_X\lambda_X)$ are both negative, indicating that electron-accepting X substituents



Scheme 2.

increase the shielding of the phosphorus atom causing the chemical shifts to decrease (Table 4). The phenomenon is well-known, and in fact van Wazer *et al.*[1] have proposed that the ^{31}P chemical shift of phosphonic acids and phosphonates offers a direct way of measuring the electron donating ability of organic radicals. The coefficient $\lambda_X\sim1.2$ shows the portion of the resonance component and it is much smaller than the respective coefficient calculated from ^{13}C chemical shift data ($\lambda\sim5$)[5] indicating that the resonance interaction described in Scheme 2, a is not very effective.

Solute–solvent interactions, especially in polar solvents may modify properties of the substituent

Table 4. Coefficients of substituent parameters σ_I and σ_R° calculated from equations (1) and (2) by multilinear regression method. In parentheses are standard deviations.

Solvent	ρ_X	$\rho_X\lambda_X$	λ_X	ρ_Y	$\rho_Y\lambda_Y$	λ_Y
50 % EtOH	−4.7(1)	−5.4(1)	1.15	0.07(5)	−0.84(6)	−12
DMSO-d_6	−4.3(2)	−5.1(2)	1.19	0.41(2)	−0.41(2)	−1.0

itself or transmission of substituent effects.[5] In the case of the phosphonates, solvent interaction with phosphoryl oxygen changes the electron environment of the phosphoryl oxygen changes the electron environment of the phosphorus atom. The hydroxylic ethanol−water mixture can form hydrogen bonds and the sulfur atom of dimethylsulfoxide can accept electrons and form a partial bond to the phosphoryl oxygen atom. All coefficients clearly change with the medium (Table 4). However in the case of the X substituent the coefficients are equally sensitive to conditions as reflected in the constancy of λ_X. The change of solvent alters the electron accepting ability of vacant phosphorus *d* orbitals by affecting the π-bond back-donation of phosphoryl oxygen. But it does not have a significant effect on the proportion of inductive and resonance components, indicating that the resonance interaction shown in Scheme 2, a is not of great importance.

The relative proportion of inductive and resonance components of the substituent Y (λ_Y) varies considerably with the medium. This is more probably due to polarization than delocalization changes of π electrons, because Modro has shown that no significant $p_\pi - d_\pi$ back-donation operates (Scheme 2,c),[8] and so solvent effects can not be detected so clearly in the resonance term.

When λ_X and λ_Y are known, the simultaneous effects of substituents X and Y can be expressed by the eq. (4), where expressions in parentheses were

$$\delta_{XY} = \delta_O + \rho'_X(\sigma_{IX} + \lambda_X\sigma^\circ_{RX}) = \rho'_Y(\sigma_{IY} + \lambda_Y\sigma^\circ_{RY}) \quad (4)$$

calculated beforehand (Table 3) and ρ' coefficients are calculated by the regression method. The dependence of ^{31}P chemical shifts on the combined substituent effects is visualized in Fig. 3.

In spite of the small number of substituents investigated and only one type of phosphonate, the method looks promising. It would seem possible to predict ^{31}P chemical shifts from σ_I and σ_R° parameters. The same σ values can be used for substituents of phenyl and phenoxy groups and only the ratio of

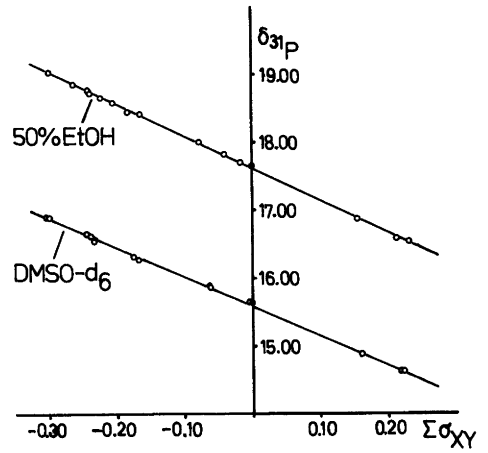


Fig. 3. Dependence of ^{31}P chemical shifts on combined substituent constants $\Sigma\sigma = \sigma_{IX} + \lambda_X\sigma^\circ_{RX} + \rho'_Y/\rho'_X(\sigma_{IY} + \lambda_Y\sigma^\circ_{RY})$ calculated using eqn. (4) and values from Table 3. In 50 % ethanol $\rho'_X = -4.75$. $\rho'_Y = 0.070$, $\delta_O = 17.63$ and $\rho'_X/\rho'_Y = -0.0147$. In dimethylsulfoxide-$d_6$ $\rho'_X = -4.29$, $\rho'_Y = 0.41$, $\delta_O = 15.60$ and $\rho'_Y/\rho'_X = -0.0956$.

parameters expressed as λ is different. Additional material is needed, however, before definite conclusions can be drawn. Parallel results have already been obtained by the author in correlation studies of decomposition reactions of the respective amine derivatives.

EXPERIMENTAL

Chemical shift measurements. The chemical shifts were measured in 50 % ethanol and dimethylsulfoxide-d_6 at 296 K. The 50 % ethanol solution was prepared by measuring exactly 50 cm^3 of ethanol and filling the flask up to the 100 cm^3 mark with water at 295 K. Samples were prepared at a concentration of 0.1 M in a 5 mm NMR tube, coaxially mounted inside an 8 mm reference tube. The reference was 0.1 M H_3PO_4 + 7 % $HClO_4$ (containing 50 % D_2O).[9] Spectra were recorded on a JEOL-

PFT-100 NMR spectrometer with 16 K data points and a spectral width of 1250 Hz.

Preparations

Phenylphosphonic dichlorides. *p*-Methylphenylphosphonous dichloride and phenylphosphonous dichloride were prepared by the Friedel-Crafts reaction,[10] and *p*-bromophenylphosphonous dichloride analogously. These intermediates were oxidized to the respective phenylphosphonic dichlorides with sulfuryl chloride in dry benzene as described for the oxidation of dialkyl hydrogenphosphonates.[11] Small amounts of the *o*-substituted derivative present with the *p*-methylphenylphosphonic dichloride disappeared in later steps. *p*-Methoxyphenylphosphonic acid prepared from phosphorus pentasulfide and anisole[12] was transformed to *p*-methoxyphenylphosphonic dichloride with thionyl chloride.

Phenyl phenylphosphonochloridates. These intermediates were prepared from the respective phenol and phenylphosphoric dichloride as described in the preparation of diphenyl phosphorochloridate.[13] The products were distilled in vacuum and yields were 40–50 %. The boiling points are shown in Table 1.

*Oxalates of 2-(*N,N-*diethylammonio)ethyl phenyl phenylphosphonates.* The products were prepared according to the method described for synthesis of dialkyl phosphate derivatives.[14] The free amines were not distilled, however, but the ether solution containing the hydrochloride precipitate was washed with 2 M sodium hydroxide solution and water and dried over potassium carbonate. Dry ether solution containing the free amine derivative was mixed with anhydrous oxalic acid in 2-propanol. The precipitated oxalates were recrystallized from acetonitrile, and yields after two recrystallizations were about 30 %. Uncorrected melting points are shown in Table 1. ^{31}P spectra revealed there to be only one phophorus peak for each sample and ^{1}H spectra were in agreement with presumed structures. The derivative X = Y = Br was not prepared because of the instability of the free amine derivative.

*2-(*N,N,N-*trimethylammonio)ethyl phenyl phenylphosphonate iodide.* The iodide salt was prepared from the respective free amine and methyl iodide in ether. ^{31}P and ^{1}H NMR spectra were in agreement with this structure and the melting point was 156–157 °C.

Acknowledgements. The financial assistance of the Neste Foundation and the Research and Science Foundation of Lääke Oy is gratefully acknowledged.

REFERENCES

1. Crutchfield, M. M., Dungan, C. H., Letcher, J. H., Mark, V. and Van Wazer, J. R. In Grayson, M. and Griffith, E. J., Eds., *Topics in Phosphorus Chemistry*, Interscience-Wiley, New York 1967, Vol. 5, p. 196.
2. Grim, S. O. and Yankowsky, A. W. *Phosphorus Sulfur 3* (1977) 191.
3. Grim, S. O., McFarlane, W. and Davidoff, E. F. *J. Org. Chem. 32* (1967) 781.
4. Payne, N. C. and Stephan, D. W. *Can J. Chem. 58* (1980) 15.
5. Bromilow, J., Brownlee, R. T. C., Lopez, V. O. and Taft, R. W. *J. Org. Chem. 44* (1979) 4766.
6. Modro, T. A. *Can. J. Chem. 55* (1977) 3681.
7. Exner, O. In Chapman, N. B. and Shorter, J., Eds., *Advances in Linear Free Energy Relationships*, Plenum, London 1972, p. 1.
8. Modro, T. A. *Phosphorus Sulfur 5* (1979) 331.
9. Glonek, T. and van Wazer, J. R. *J. Magn. Reson. 13* (1974) 390.
10. Houben-Weyl, *Methoden der Organischen Chemie*, Thieme, Stuttgart 1963, Band XII/1, p. 315.
11. Sosnovsky, G. and Zaret, E. H. *J. Org. Chem. 34* (1969) 968.
12. Ref. 10., p. 357.
13. Briegl, P. and Müller, H. *Ber. 72* (1939) 2121.
14. Tammelin, L. E. *Acta Chem. Scand. 11* (1957) 1340.

Received August 20, 1980.