JOURNAL OF PHYSICAL ORGANIC CHEMISTRY, VOL. 10, 221–228 (1997)

SOLVENT EFFECTS ON REACTIONS OF HYDROXIDE AND OXIMATE IONS WITH PHOSPHORUS(V) ESTERS

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Second-order rate constants of reactions of OH^-, 2,3-butanedionemonooximate and 2-hydroxybenzaldoximate ions with aryl phosphate, phosphinate and thioarylphosphinate esters go through minima with decreasing water content of aqueous acetonitrile, *tert*-butyl alcohol and *N*-methyl-2-pyrrolidone. For reactions in H_2O–MeCN the solvent effects are analyzed in terms of activity coefficients of the anionic nucleophiles and transition states. In the drier solvents partial desolvation of the nucleophiles increases rates. Nucleophilicities of several oximates and inorganic anions are compared in water. © 1997 by John Wiley & Sons, Ltd.

J. Phys. Org. Chem. **10**, 221–228 (1997) No. of Figures: 3 No. of Tables: 9 No. of References: 29

Keywords: solvent effects; hydroxide; oximates; phosphorus(V) esters; nucleophilicity

Received 14 August 1996; revised October 1996; accepted 18 October 1996

INTRODUCTION

Second-order rate constants of reactions of OH^- with phosphorus(V) esters of phenols or thiols in water go through minima on addition of either acetonitrile (MeCN) or *tert*-butyl alcohol (*t*–BuOH).[1] These observations do not fit either qualitative treatments of kinetic solvent effects based on the Hughes–Ingold rules, or quantitative treatments that relate rate constants of ion–molecule interactions to solvent dielectric constants.[2, 3] However, these treatments are satisfactory for many reactions, e.g. of nucleophiles with alkyl halides. Other treatments focus on solvent electrophilicity, nucleophilicity, polarizability and cavity formation,[4] on donor–acceptor properties[5] or on solvent nucleophilicity and ionizing power,[6] with the aim of identifying the factors that control medium effects on rates of nucleophilic reactions.

We previously proposed that the initial rate decrease on addition of an organic solvent is due to stabilization of the relatively hydrophobic esters and the high rate constant in the drier solvents stems from the well characterized desolvation of anions in solvents of low water content.[2–7] Activity coefficients of the esters decreased sharply on addition of MeCN to water.[1]

Nucleophilic attack is a potentially useful method of destruction of phosphorus(V) nerve agents,[8] but some of them are sparingly water soluble and solubilizing agents, either organic solvents or association colloids, e.g. micelles- or microemulsions, are needed.[8, 9] We have now extended our work to other nucleophiles, in particular to oximate ions which are very reactive towards acyl and phosphorus(V) centers.[10–12] Nucleophilic reactions of oximate ions, especially at acyl centers,[11] have been studied in detail and there are data for reactions of other nucleophilic anions, e.g. F^-, and aryloxide ions with various phosphorus(V) derivatives.[10b, 13] We initially examined the reactions of several nucleophiles and esters in water containing small amounts of MeCN in order to select reactions which would be convenient for a general study of kinetic solvent effects. We chose oximate ions and *p*-nitrophenyl and *p*-nitrothiophenyl derivatives for the work. The hydration of oximate ions should differ from that of OH^- and a variety of structures can be selected.

Activity coefficients of most of the esters had been measured by partitioning into pentane.[1] This method cannot be used with aqueous *t*-BuOH because the organic solvents are miscible. We hoped to be able to use aqueous *N*-methyl-2-pyrrolidone (NMP) in this work because it is miscible with water and is non-toxic,[14] but is partially miscible with pentane and we could not determine activity coefficients in aqueous NMP and have only kinetic data in this system.

Reactions of oximate ions with *p*-nitrophenyl diphenylphosphate, *p*-nitrophenyl diphenylphosphinate and *p*-nitrophenyl ethylphenylphosphinate [$(PhO)_2POOAr$, Ph_2POOAr and PhEtPOOAr, respectively, where Ar = 4-$NO_2C_6H_4$] and *p*-nitrothiophenyl diphenylphosphinate (Ph_2POSAr), were followed over a range of solvent composition. We had earlier followed the reactions of most of these esters in aqueous MeCN and *t*-BuOH.[1] The oximates used in the present work were 2,3-butanedionemonooximate (BDO) and 2-hydroxybenzaldoximate

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Contract grant sponsor: US Army Research Office.

CCC 0894–3230/97/040221–08 $17.50

(BAO–OH). Reactions with the anions of the following oximes were followed only in H_2O plus a small amount of MeCN: benzaldoxime (BAO), 2-methoxybenzaldoxime (BAO–OMe) and α,α,α-trifluoroacetophenone oxime (TFAO). We examined reactions of $(PhO)_2POSAr$, $(PhO)_2POOC_6H_32,4\text{–}(NO_2)_2$ and $Ph_2POOC_6H_3\text{-}2,4\text{-}(NO_2)_2$ with some nucleophiles, but only in solvents of high water content, and because of the rapid spontaneous hydrolyses we could not estimate activity coefficients of these esters in mixed solvents.

Second-order rate constants, k_2, of reactions of OH^- in aqueous MeCN were analyzed by using the Brønsted–Bjerrum rate equation.[1, 3, 15]

$$\frac{k_2}{k_2^0\gamma_s}=\frac{\gamma_{Nu}}{\gamma_{\mp}} \qquad (1)$$

where s is substrate and Nu anionic nucleophile. The second-order rate constant, k_2^0, is in water, which is the standard state, and $\gamma_{\mp}$ is the activity coefficient of the activated complex. The substrate activity coefficient, γ_s, was measured in up to 60 vol.% MeCN, which was the driest solvent for which we could determine γ_s. Plots of $\log(\gamma_{OH}/\gamma_{\mp})$ against $\log\gamma_s$ were linear, i.e.

$$\log(\gamma_{OH}/\gamma_{\mp})=a\log\gamma_s \qquad (2)$$

with $a\approx-0.7$ for several esters.[1]

Combining equations (1) and (2) gives

$$\log(k_2/k_2^0)=(1+a)\log\gamma_s=\frac{1+a}{a}\log(\gamma_{OH}/\gamma_{\mp}) \qquad (3)$$

We interpreted these results on the assumption that a decrease in the water content of the solvent decreases k_2 by decreasing γ_s, i.e. by lowering the free energy of the substrate, but this inhibition is partially offset by stabilization of the bulky monoanionic transition state (decrease of $\gamma_{\mp}$). We also assumed that γ_{OH} does not decrease significantly except in the drier solvents. In 60 vol.% MeCN the mole fraction of H_2O $\chi_{H_2O}\approx 0{\cdot}65$ and OH^- should be strongly hydrated.

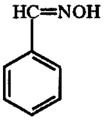
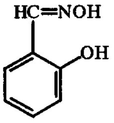
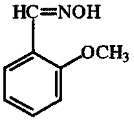
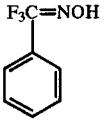
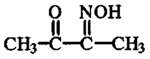
We planned to test this simple model for reactions of oximate ions which should be less hydrophilic than OH^-.

EXPERIMENTAL

Materials. The esters were samples used earlier or were prepared as described.[1, 16–18] 2-Hydroxybenzaldoxime (BAO–OH) (Aldrich) was recrystallized from hexane–$CHCl_3$, m.p. 60 °C and is the *anti*-isomer.[19] *syn*-Benzaldoxime (BAO) (Aldrich) was used as received. α,α,α-Trifluoroacetophenone oxime (TFAO) was prepared as described by Salvador *et al.*[20] and was an equimolar *syn–anti* mixture.[21a] 2-Methoxybenzaldoxime (BAO–OMe) was prepared as described[22] and was recrystallized from EtOH, m.p. 90 °C. 2,3-Butanedionemonooxime (BDO) was a gift from Dr Yu-Chu Yang. Organic solvents were redistilled and it was necessary to use samples of *N*-methyl-2-pyrrolidone (NMP) that had been freshly distilled *in vacuo*. Kinetic solutions were prepared using CO_2-free, distilled, deionized water.

Kinetics. Reactions of OH^- and other inorganic anions were followed spectrophotometrically as described.[1] Reactions with oximate or phenoxide ion were followed only with esters that contained nitro groups because these anionic nucleophiles absorb strongly in the UV region and interfere with spectral data for esters with EtS or PhS leaving groups. We generally carried out reactions with phenoxide or oximate ions by taking an insufficiency of OH^-. In water OH^- is then extensively protonated and there is only a minor contribution of reaction of residual OH^-. The extent of protonation of OH^- decreases in the mixed solvents and it became necessry to correct for reaction of OH^-. Extinction coefficients of the oximates were determined and from the absorbances of the kinetic solutions, before addition of substrate, we estimated the concentrations of the

Table 1. Literature and experimentally observed pK_a values of oximes

Oxime	Abbreviation	Observed	Literature
	BAO	10·86	
	BAO–OH	8·86[a]	9·17[b]
	BAO–OMe	10·72	
	TFAO	8·78	9·18[c]
 $CH_3-C(=O)-C(=NOH)-CH_3$	BDO	9·32	9·38[b]

[a] The second pK_a of the OH group is 11·54.
[b] In 0·1 M KCl, determined potentiometrically.[21b]
[c] In 0·2 M KCl, 12 vol.% EtOH, determined potentiometrically.[21a]

Table 2. Second-order rate constants of reactions with various nucleophiles in water[a]

Nucleophile	$(PhO)_2POOAr$	Ph_2POOAr	Ph(Et)POOAr	$(PhO)_2POSAr$	Ph_2POSAr	$(PhO)_2POOAr'$	Ph_2POOAr'
OH^-	0·52	18·3	10·4	43	21·2	6·03	26·1
F^-	0·11	0·81		0·048	5·1	6·3	118
$B_4O_7^{2-}$		0·029		0·1	0·061	0·073	1·18
PhO^-	0·032[c]	0·59[d, e]		0·24	2·9		45·0[e]
BDO	0·62	4·00	1·55		17·8	21·5	240
BAO–OH	2·01	47·1	5·1		13·5		
BAO–OMe[b]	0·45	6·26			25·0		
TFAO[b]		1·1			2·84		
BAO[b]					35·0		

[a] Second-order rate constants, $M^{-1}\ s^{-1}$ at 25·0 °C with 0·4 vol.% MeCN; OAr, SAr and OAr' refer to OC_6H-4-NO_2, SC_6H_5-4-NO_2 and OC_6H_4-2,4-$(NO_2)_2$ as leaving groups, respectively.

[b] With 4·2 vol.% MeCN.

[c] Ref 13b.

[d] In 0·1 M KCl, borate buffer.

[e] 13c.

oximate ions and by mass balance those of residual OH^-. Allowance was made for the contribution of reaction with OH^- based on known second-order rate constants. The general procedure is illustrated with BAO–OH in H_2O–MeCN, where in H_2O with the oximate ion $\lambda_{max} = 352$ nm, and ε at this wavelength decreased from 5175 $M^{-1}\ cm^{-1}$ in 0·3 vol.% MeCN to 4250 $M^{-1}\ cm^{-1}$ in 84·1 vol.% MeCN and was measured for intermediate solvent compositions. These measurements were made in 2 mm cuvettes and reactions of the esters were followed in 1 cm cuvettes. Unless specified, the esters were added in MeCN and the kinetic solution in H_2O contained 0·4 vol.% MeCN.

A few reactions were carried out in carbonate buffer (0.024 M) and we estimated the concentration of oximate ion spectrophotometrically in the kinetic solutions by using short pathlength cuvettes and corrected for reaction in the buffer in the absence of oxime.

Dissociation constants. Dissociation constants were determined in 0·5 vol.% MeCN, where pH can be measured directly and was varied by addition of OH^-. Values of pK_a were calculated by using the equations

$$\mathrm{pH} = \mathrm{p}K_a + \log([\mathrm{Ox}^-]/[\mathrm{HOx}]) \qquad (4)$$

$$[\mathrm{Ox}^-] = \frac{\mathrm{Abs} - \varepsilon_{\mathrm{HOx}}[\mathrm{HOx}]_T}{\varepsilon_{\mathrm{Ox}^-} - \varepsilon_{\mathrm{HOx}}} \qquad (5)$$

where Ox^- and HOx are oximate and oxime, respectively, and subscript T denotes total material.

Values of pK_a (Table 1) are in reasonable agreement with literature values, where available, in view of differences in methods and media composition.

Activity coefficients. We followed the method used earlier,[1] by partitioning Ph(Et)POOAr between pentane and H_2O–MeCN.[23]

RESULTS AND DISCUSSION

Kinetics

We examined several combinations of nucleophiles and substrates in order to select those suitable for a systematic study of medium effects. Second-order rate constants for reactions of nucleophilic anions are given in Table 2. Some of these reactions had been followed earlier, although in some cases in different solvents to those used here.[13, 24] Our rate data agree reasonably well with earlier results for reactions of OH^- and F^- with $(PhO)_2POOAr$ and $(Ph)_2POOAr$. Comparison with data for the reaction with PhO^- in mixed solvents shows that it is inhibited by addition of organic solvents to water.[13b, 24]

Table 3. Second-order rate constants of reaction of OH^- with Ph(Et)POOAr and substrate activity coefficients in H_2O–MeCN at 25·0 °C

	Vol.% MeCN							
Parameter	0	0·4	10·4	20·3	40·2	60·2	80·1	84·1
χ_{MeCN}	0		0·038	0·081	0·189	0·343	0·582	0·646
k_2 ($M^{-1}\ s^{-1}$)	10·5	10·4	9·35	8·55	8·05	8.05	14·6	22·8
γ_s	1·0	0·94	0·41	0·172	0·0257	0·0182		

Table 4. Second-order rate constants of reaction of OH^- with Ph(Et)POOAr in H_2O–*t*-BuOH at 25·0 °C

	Vol.% *t*-BuOH				
Parameter	0	16·5	32·0	56·9	75·1
$\chi_{t\text{-BuOH}}$		0·046	0·103	0·243	0·423
k_2 ($\text{M}^{-1}\,\text{s}^{-1}$)	10·5	6·84	5·50	8·79	23·9

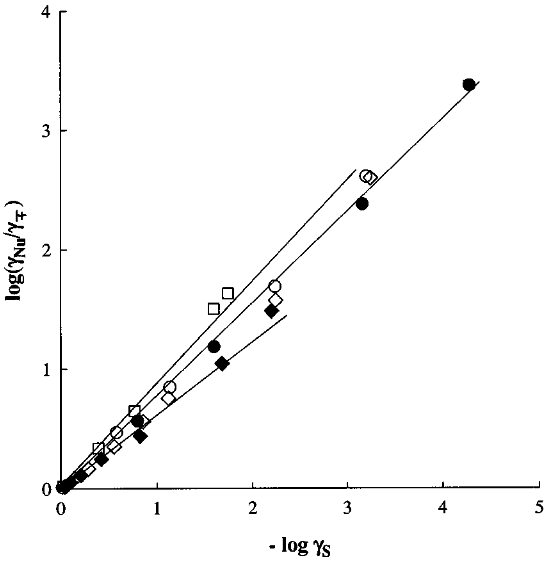


Figure 1. Relationships between log ($\gamma_{Nu}/\gamma_{\mp}$) and log γ_s for reactions with OH^- in H_2O–MeCN: (●) $(PhO)_2POOAr$; (○) Ph_2POOAr; (◇) Ph_2POSPh; (◆) Ph_2POSEt; (□) Ph(Et)POOAr

The sequence of nucleophilicities, relative to OH^-, is in qualitative agreement with those observed earlier. For example, oximate ions and to a lesser extent PhO^-, are more reactive than predicted by simple Brønsted relations between nucleophilicity and basicity, i.e. they behave as α-effect nucleophiles.[10, 11] However, with 2,4-dinitrophenoxy leaving groups F^- is more reactive than OH^-, even though it does not fit the criteria for an α-effect nucleophile.

Except for reaction of OH^- with $(PhO)_2POSAr$ and Ph_2POSAr, phosphinates are more reactive than phosphates, in agreement with extensive evidence[1, 16–18] (the product is $(NO_2)C_6H_4S^-$ based on the ^1H NMR spectrum). The higher reactivity of phosphinates has been ascribed to p–d orbital overlap in the phosphates,[16] but if reactions are concerted[13c, 24] and the transition states are similar to (hypothetical) trigonal bipyramidal intermediates, placing phenyl groups into equatorial positions will be preferred energetically over placing the more electronegative phenoxy groups into these positions.[25] In addition, extents of bond making and breaking in the transition state should depend on the nature of the entering and leaving groups and those attached to the reaction center.

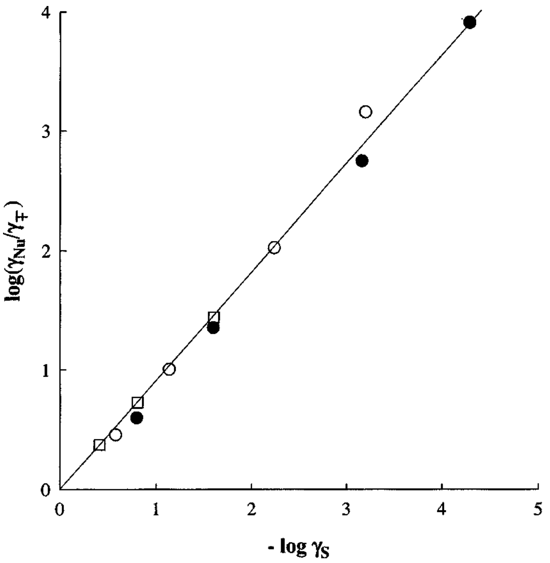


Figure 2. Relationships between log($\gamma_{Nu}/\gamma_{\mp}$) and log γ_s for reactions with 2,3-butanedionemonooximate ion (BDO) in H_2O–MeCN. Symbols as in Fig. 1

In agreement with earlier results, thioaryl are more reactive than the corresponding aryloxy derivatives, although rate differences are small, relative to differences in acidities of phenols and thiophenols.[16–18] However, relative reactivities depend on the nucleophile. The 2,4-dinitrophenoxy derivatives are not very much more reactive than the corresponding 4-nitrophenoxy derivatives towards OH^- and $B_4O_7^{2-}$, but the rate differences are larger for reactions of F^- and the organic anions, pointing to differences in the relative importance of bond making and breaking in either stepwise or concerted reactions. Conformations of transition states and (hypothetical) intermediates probably depend on reactant structure and solvent composition,[13, 16–18, 25] and it is difficult to make simple generalizations regarding relative rates of the reactions noted in Table 2. The anions generally react nucleophilically, although borate ion may be acting as a general base. For an example of general base-catalyzed dephosphorylation, see Ref. 26.

Nucleophilicities of oximates and other anions are often related to basicities,[10, 11] but solvent interactions can be of major importance.[27, 28] In terms of basicities (Table 1), BAO–OH is a better nucleophile than either BAO or BAO–OMe, probably because its *anti* configuration,[19] reduces steric crowding at the reaction center, but the rate differences are small (Table 2) so the phenolic hydroxyl group is not significantly affecting nucleophilicity. BDO is a better nucleophile than TFAO and the relatively low solubility of TFAO in H_2O with 0·4 vol.% MeCN was inconvenient

Table 5. Second-order rate constants of reaction with 2,3-butanedionemonooximate ion (BDO) and substrate activity coefficients in H_2O–MeCN[a]

Vol.% MeCN	χ_{MeCN}	$(PhO)_2POOAr$ k_2	$(PhO)_2POOAr$ γ_s	Ph_2POOAr k_2	Ph_2POOAr γ_s	Ph(Et)POOAr k_2	Ph(Et)POOAr γ_s	Ph_2POSAr k_2
0		0·635[b]		4·29[b]		1·6[b]		18·0[b]
10·4	0·038	0·400 (0·63)	0·159	3·22 (0·75)	0·263	1·47 (0·92)	0·389	15·6 (0·87)
20·3	0·081	0·358 (0·56)	0·025	3·13 (0·73)	0·073	1·35 (0·84)	0·157	17·4 (0·97)
40·2	0·189	0·243 (0·38)	$6{\cdot}9\times10^{-4}$	2·60 (0·66)	$5{\cdot}8\times10^{+3}$	1·10 (0·69)	0·025	18·3 (1·0)
60·2	0·343	0·262 (0·41)	$5{\cdot}2\times10^{-5}$	3·83 (0·89)	$6{\cdot}3\times10^{-4}$	2·08 (1·3)		34·5 (1·9)
70·1	0·448					3·97 (2·5)		44·5 (2·5)
74·1	0·498			5·95 (1·4)				
86·1	0·680	0·925 (1·5)		11·6 (2·7)				140 (7·8)
88·9	0·736			44·0 (10)				214 (12)

[a] Rate constants, $M^{-1}\,s^{-1}$, at 25·0 °C and substrate activity coefficients. Values of k_2/k_2^0 are given in parentheses.
[b] Values extrapolated from data with MeCN > 0·4 vol.%.

Table 6. Second-order rate constants of reactions with 2-hydroxybenzaldoximate ion (BAO–OH) in H_2O–MeCN[a]

Vol.% MeCN	χ_{MeCN}	$(PhO)_2POOAr$	Ph_2POOAr	Ph(Et)POOAr	Ph_2POSAr
0		2·06[b]	48·3[b]	5·10[b]	136[b]
10·4	0·038	1·43 (0·69)	29·0 (0·6)	4·26 (0·83)	117 (0·86)
20·3	0·081	1·12 (0·54)	19·4 (0·4)	4·45 (0·87)	106 (0·78)
40·2	0·189	0·645 (0·31)	16·0 (0·33)	5·45 (1·07)	90·7 (0·67)
60·2	0·343	0·672 (0·33)	18·3 (0·38)	7·13 (1·40)	97·3 (0·71)
70·1	0·448			10·7 (2·10)	
80·1	0·581	0·958 (0·46)			210 (1·54)
84·1	0·646		35·0 (0·73)		340 (2·50)
90·0	0·756	2·67 (1·3)			

[a] Rate constants, $M^{-1}\,s^{-1}$, at 25·0 °C. Values of k_2/k_2^0 are given in parentheses.
[b] Values extrapolated from data with MeCN > 0·4 vol.%.

Table 7. Second-order rate constants of reaction with hydroxide and 2,3-butanedionemonooximate ion (BDO) in H_2O–N-methyl-2-pyrrolidone[a]

Vol.% NMP	χ_{NMP}	$(PhO)_2POOAr$ OH^-	$(PhO)_2POOAr$ BDO	Ph_2POOAr OH^-	Ph_2POOAr BDO	Ph(Et)POOAr OH^-	Ph(Et)POOAr BDO
0		0·52	0·635	18·6	4·29	10·5	1·60
10	0·0204	0·322 (0·62)	0·420 (0·66)	12·0 (0·64)	2·75 (0·64)	7·37 (0·7)	1·11 (0·69)
20	0·0447	0·320 (0·61)	0·244 (0·38)	8·00 (0·43)	2·08 (0·48)	8·80 (0·84)	1·05 (0·66)
40	0·111	0·465 (0·89)	0·278 (0·44)	6·63 (0·36)	1·93 (0·45)	14·4 (1·4)	3·85 (2·4)
50	0·158				2·66 (0·62)		
60	0·219	0·915 (1·76)	0·544 (0·86)	11·2 (0·60	6·44 (1·5)	34·6 (3·3)	9·59 (6·0)
80	0·427	3·48 (6·69)	1·24 (1·95)	48·0 (2·6)	49·2 (11·5)	73·4 (7·0)	

[a] Rate constants, $M^{-1}\,s^{-1}$, at 25·0 °C. Values of k_2/k_2^0 are given in parentheses.

because we are considering rate constants relative to those in water. Based on all these data we selected BDO and BAO–OH for an extended study of kinetic solvent effects.

Nucleophilicities of oximate ions should depend on their configuration and therefore it is probably not useful to attempt to rationalize relationships between reactivity and structure in the oximate ions that we examined.

Analysis of kinetic solvent effects in H_2O–MeCN

The earlier observation[1] of a linear relationship between $\log(\gamma_{OH}/\gamma_{\mp})$, or $\log(k_2/k_2^0)$ and $\log \gamma_s$ [equations (2) and (3)] for reaction with OH^- in H_2O–MeCN has now been extended to the reaction of Ph(Et)POOAr (Tables 3 and 4) and a plot of $\log(\gamma_{OH}/\gamma_{\mp})$ against $\log \gamma_s$ has a slope $a = -0{\cdot}9$

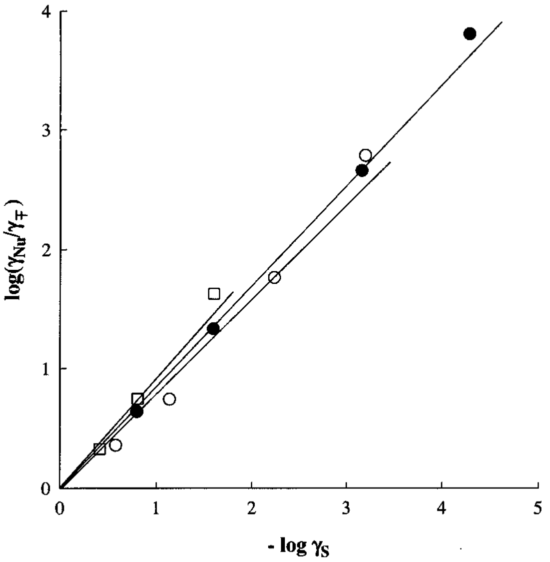


Figure 3. Relationships between $\log(\gamma_{Nu}/\gamma_\mp)$ and $\log\ \gamma_a$ for reactions with 2-hydroxybenzaldoximate ion (BAO–OH) in H_2O–MeCN. Symbols as in Fig. 1

(Figure 1) compared with $a \approx -0{\cdot}75$ for reactions of $(PhO)_2POOAr$, Ph_2POOAr and Ph_2POSPh and $a = -0{\cdot}65$ for Ph_2POSEt.[1] For reaction of Ph(Et)POOAr, equations (2) and (3) give

$$\log(k_2/k_2^0) = 0.1 \log \gamma_s = -0.11 \log(\gamma_{OH}/\gamma_\mp) \qquad (6)$$

We could follow the reactions of oximate ions spectrophotometrically only with substrates that had 4-nitrophenoxy or 4-nitrothiophenyl leaving groups and the relatively fast spontaneous hydrolyses of Ph_2POSAr and 2,4-dinitrophenyl derivatives prevented us from measuring their activity coefficients.[1] Therefore, our quantitative analysis of reactions with oximates is restricted to $(PhO)_2POOAr$, Ph_2POOAr and Ph(Et)POOAr (Table 5).

For reactions with BDO plots of $\log(\gamma_{Nuc}/\gamma_\mp)$ against $\log\ \gamma_s$ are approximately colinear with slope $a = -0{\cdot}85$, which is similar to the value for reaction of OH^- with Ph(Et)POOAr (Figures 1 and 2), based on rate data in Table 4.

For these reactions of BDO:

$$\log(k_2/k_2^0) = 0{\cdot}15 \log \gamma_s = -0{\cdot}18 \log(\gamma_{OH}/\gamma_\mp) \qquad (7)$$

The situation is similar to reactions of BAO–OH, (Table 6 and Fig. 3) where values of a [equation (2)] are $-0{\cdot}9$, $-0{\cdot}85$ and *ca* $-0{\cdot}8$ for Ph(Et)POOAr, $(PhO)_2POOAr$ and Ph_2POOAr, respectively, giving the following relationships:

Ph(Et)POOAr $$\log(k_2/k_2^0) = 0{\cdot}1 \log \gamma_s = -0{\cdot}11 \log(\gamma_{Nuc}/\gamma_\mp) \qquad (8)$$

$(PhO)_2POOAr$ $$\log(k_2/k_2^0) = 0{\cdot}15 \log \gamma_s = -0{\cdot}18 \log(\gamma_{Nuc}/\gamma_\mp) \qquad (9)$$

Ph_2POOAr $$\log(k_2/k_2^0) = 0{\cdot}2 \log \gamma_s = -0{\cdot}25 \log(\gamma_{Nuc}/\gamma_\mp) \qquad (10)$$

Table 8. Second-order rate constants of reactions with 2,3-butanedionemonooximate ion (BDO) in H_2O–*t*-BuOH[a]

Vol.% *t*-BuOH	$\chi_{t\text{-BuOH}}$	$(PhO)_2POOAr$	Ph_2POOAr	Ph(Et)POOAr	Ph_2POSAr
0		0·635	4·29	1·60	18·0
17·2	0·048	0·265 (0·42)	1·21 (0·28)	1·50 (0·94)	23·0 (1·3)
34·9	0·115	0·165 (0·20)	0·682 (0·16)	1·80 (1·12)	28·0 (1·6)
58·1	0·252	0·183(0·29)	0·893 (0·21)	2,68 (1·67)	36·2 (2·0)
82·2	0·529	0·310 (0·49)	2·60 (0·61)		62·0 (3·4)

[a] Rate constants, $M^{-1}\ s^{-1}$, at 25·0 °C. Values of k_2/k_2^0 are given in parentheses.

Table 9. Second-order rate constants of reactions with 2-hydroxybenzaldoximate ion (BAO–OH) in H_2O–*t*-BuOH[a]

Vol.% *t*-BuOH	$\chi_{t\text{-BuOH}}$	$(PhO)_2POOAr$	Ph_2POOAr	Ph(Et)POOAr	Ph_2POSAr
0		2·06	48·3	5·10	136
7·9	0·021	1·19(0·58)	30·5 (0·63)	4·31(0·85)	83·5 (0·61)
16·0	0·046	0·815 (0·40)	11·3 (0·23)	4·10 (0·80)	81·5 (0·60)
32·9	0·111	0·405 (0·20)	4·55 (0·094)	4·80 (0·94)	43·2 (0·32)
51·4	0·204		2·07(0·043)		
52·1	0·257	0·398 (0·190	2·02 (0·042)	5·10 (1·0)	46·0 (0·34)
73·3	0·400	4·93 (0·10)	7·06 (1·39)	95·6 (0·70)	
76·2	0·411	0·591(0·29)			

[a] Rate constants, $M^{-1}\ s^{-1}$, at 25·0 °C. Values of k_2/k_2^0 are given in parentheses.

The corresponding relationships for reactions of OH^- with $(PhO)_2POOAr$, Ph_2POOAr and Ph_2POSPh are

$$\log(k_2/k_2^0) = 0{\cdot}25 \log \gamma_s = -0{\cdot}33 \log(\gamma_{OH}/\gamma_s) \qquad (11)$$

and for reaction with Ph_2POSEt:

$$\log(k_2/k_2^0) = 0{\cdot}35 \log \gamma_s = -0{\cdot}54 \log(\gamma_{OH}/\gamma_s) \qquad (12)$$

For most of these reactions the relationships between rate constants and relative activity coefficients of the anionic nucleophiles and the transition states are similar, despite marked differences in the structures of the nucleophiles. The coefficients of $\log \gamma_s$ and $\log(\gamma_{Nuc}/\gamma_{\mp})$ are numerically similar, but of opposite sign, which means that addition of MeCN inhibits reaction by lowering the free energies of the esters and accelerates it by increasing $\gamma_{Nuc}/\gamma_{\mp}$. This partial compensation is not very sensitive to the structures of the esters or the nucleophiles, despite marked differences in their solvation requirements. However, a decrease in the water content of the solvent always stabilizes the bulky anionic transition state relative to the anionic nucleophile, regardless of the structure of the latter, as predicted by qualitative and quantitative treatments.[2, 3] The failure of these simple treatments to fit the kinetic solvent effects is due to their neglect of medium effects on the free energies of the esters.

In the drier solvents desolvation of the anionic nucleophiles gives sharp increases in k_2, depending on the effect of the organic solvent on the ability of H_2O to hydrogen bond to the anion. In these solvents we expect that γ_s and $\gamma_{\mp}$ will become similar because the transition state is a bulky, low-charge density, anion and solvation by organic solvents should not be very sensitive to charge.

The similar behaviors of OH^- and oximate ions of different structures may arise because the charge in the latter is largely on oxygen and strongly charge-delocalized oxyanions may behave differently. The rate minima are less evident for reactions with oximate ions than with OH^-, except for reactions with Ph(Et)POOAr (Tables 3–5 and Ref. 1). These qualitative observations accord with the slopes, $-a$, of plots of $\log(\gamma_{Nuc}/\gamma_{\mp})$ against $\log \gamma_s$, tending toward unity (Nuc = OH^- or oximate) as the ester becomes more and the nucleophile less hydrophilic. There is then more compensation between the solvation requirements of the reactants and the transition state until in the drier solvents there is dominant desolvation and destabilization of the anionic nucleophile (increase in γ_{Nuc}). The rates then increase very sharply and deviations from predictions based on the qualitative solvent rules decrease.[2, 3]

Kinetic effects of organic solvents

Second-order rate constants for reactions in aqueous *t*-BuOH and NMP are given in Tables 4 and 7–9. Qualitatively these solvents and MeCN behave similarly, but there are differences in the extents of rate minima and increases in the drier solvents.

A number of physical properties are used as indicators of kinetic solvent effects. The dielectric constant of *t*-BuOH (12·47) is much lower than those of MeCN (35·94) and NMP (32·2), but the corresponding E_T^N values are 0·389, 0·460 and 0·355.[3] Based on solvatochromic scales of pure solvents, *t*-BuOH is a better hydrogen bond donor and acceptor than MeCN, but is less polarizable.[4]

For reactions with OH^- values of k_2/k_2^0 for given mole fractions of *t*-BuOH or MeCN are similar, although rate minima appear at lower mole fractions of *t*-BuOH than MeCN. The behavior of NMP is different, because the values of k_2/k_2^0 increase sharply with $\chi_{NMP} > 0{\cdot}1$, especially with the *p*-nitrophenoxy derivatives (Table 7).

In reactions of BDO, MeCN and *t*-BuOH affect k_2/k_2^0 similarly, but the rates increase much more sharply in the drier solvents than for reactions of OH^- (Tables 5 and 8). As for reactions with OH^-, the rates increase very sharply with increasing amount of NMP (Table 7). The ability of NMP to increase nucleophilicity is understandable because it, like DMF and DMSO, should be a strong hydrogen bond acceptor,[3, 4, 7, 29] and reduce the ability of H_2O to deactivate nucleophilic anions. The only limitation in the use of NMP as a kinetic solvent is that we had to use freshly distilled material in obtaining consistent kinetic data (Experimental).

Values of k_2/k_2^0 in the drier solvents depend on the nucleophile, the leaving group and the organic solvent. For given reactants these values are always larger in H_2O–NMP and H_2O–MeCN than in H_2O–*t*-BuOH, reflecting the ability of *t*-BuOH to hydrogen bond, albeit weakly, to anions.[4] The consequent deactivation should be more important for reactions of OH^- than of the oximate ions, owing to differences in hydrogen bond acceptance which make it more difficult to desolvate OH^- than an oximate ion. Hydrogen bonding to the leaving oxide or thiolate ion (electrophilic assistance) is probably not very important, because although arene thiols are much more acidic than the corresponding phenols, this difference is not reflected in the reactivities of the phosphorus(V) esters. Electron-withdrawing substituents increase the acidities of the phenols or thiols much more than reactivities of the esters.[16–18]

Terrier and co-workers have observed non-linear Brønsted plots in deacylations by oximate ions[11] and in reactions of aryloxide ions with bis(4-nitrophenyl)phenylphosphonate in mixed solvents.[28] They explained these results in terms of a required partial desolvation of the nucleophile, based on modified Brønsted plots which take medium effects into account.[27] The solvation term, as in our experiments, depends on the nucleophile and the organic cosolvent.

ACKNOWLEDGEMENT

Support by the US Army Research Office is gratefully acknowledged.

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