

Kinetic Studies of the Solvolyses of 4-Nitrophenyl Phenyl Thiophosphorochloridate

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Rates of solvolyses of 4-nitrophenyl phenyl thiophosphorochloridate (4-NO₂PhOP(S)(Cl)OPh, **1**) in ethanol, methanol, and aqueous binary mixtures incorporating ethanol, methanol, acetone, and 2,2,2-trifluoroethanol (TFE) are reported. Thermodynamic parameters were determined at several temperatures in three representative solvents. The extended Grunwald-Winstein equation was applied to 29 solvents and the correlation coefficient (*R*) showed 0.959. The sensitivities (*l* = 1.37 and *m* = 0.62) are similar to those obtained for diphenyl thiophosphorochloridate ((PhO)₂PSCl, **2**), diphenyl phosphorochloridate ((PhO)₂POCl, **3**), diphenyl phosphinic chloride (Ph₂POCl, **4**), and diphenyl thiophosphinic chloride (Ph₂PSCl, **5**). The solvolytic reaction mechanism of 4-nitrophenyl phenyl thiophosphorochloridate (**1**) is suggested to be proceeded a S_N2 process as previously reported result. The activation enthalpies are shown as slightly low as ΔH[‡] = 9.62 to 11.9 kcal·mol⁻¹ and the activation entropies are shown as slightly high negative value as ΔS[‡] = -34.1 to -44.9 cal·mol⁻¹·K⁻¹ compared to the expected S_N2 reaction mechanism. Kinetic solvent isotope effects are accord with a typical S_N2 mechanism as shown in the range of 2.41 in MeOH/MeOD and 2.57 in H₂O/D₂O solvent mixtures.

Key Words: 4-Nitrophenyl phenyl thiophosphorochloridate. Extended Grunwald-Winstein equation, S_N2 mechanism. Kinetic solvent isotope effects

Introduction

There have been several studies of the kinetics of nucleophilic substitution reaction of phosphoryl transfer reactions. A considerable amount of work has been carried out to clarify the problem whether phosphoryl transfer reactions proceed concertedly with a single transition state (TS) or *via* a stepwise mechanism with a pentacoordinated phosphorane intermediate.¹

Some researchers^{2a,b} measured the rates of the pyridinolyses of phosphoryl pyridinium compounds, and discussed the reaction mechanism using the slopes, β_{int} and β_g of the Brønsted plots, as a probe of the existence of intermediates in phosphoryl transfer reactions. They suggested mostly to be proceeded by a concerted substitution mechanism for the phosphoryl transfer reaction and the reaction is "exploded" a general TS shown as weak bonds between the distances of attacking group and leaving group.

The extended Grunwald-Winstein equation³⁻⁵ is used to correlate the specific rates of solvolysis reactions in terms of solvent ionizing power³ and solvent nucleophilicity.^{4a} In equation (1), *k* and *k*₀ represent the specific rate of solvolysis in a given solvent and one in the standard solvent (80% ethanol), respectively; *l* represents the sensitivity to changes in solvent nucleophilicity (N_T); *m* represents the sensitivity to changes in solvent ionizing power (Y_X, for a leaving group X); *c* represents a constant (residual) term.

$$\log(k/k_0) = l N_T + m Y_X + c \quad (1)$$

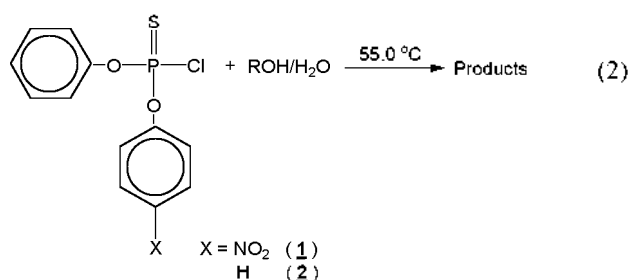
Although the equation was initially developed for the nucleophilic attack at sp³-carbon, the scales, N_T and Y_X are

also applied successfully to the nucleophilic attack sp²-carbon,⁵ phosphorus,^{6,7} and sulfur.⁸ In the reported studies, a direct S_N2 reaction mechanism is shown for the solvolytic reactions of dialkyl,⁷ diaryl⁹ and phosphorochloridates possessing phosphorus reaction center as shown a good correlation fitted into the equation.

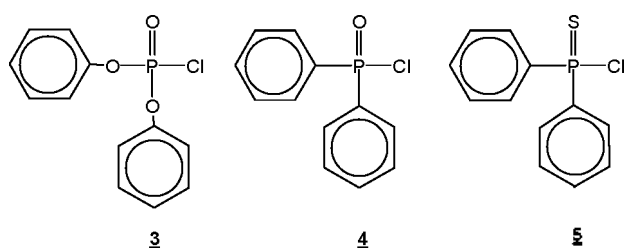
The direct S_N2 mechanism for the solvolytic reactions have been examined for the substrates, (PhO)₂POCl, **3**,¹⁰ diaryl⁹ and dimethyl⁷ phosphorochloridates, (RO)₂POCl, the sulfur-for-oxygen substituted dimethyl phosphorochloridothionate, (MeO)₂PSCl,⁷ N,N,N',N'-tetramethyldiamido-phosphorochloridate, (Me₂N)₂POCl,⁶ and diphenylphosphinyl chloride, Ph₂POCl, **4**,^{11a} previously by Kevill and co-workers. The extended Grunwald-Winstein equation plots for solvolyses of those substrates containing the P-atom as the reaction center led to acceptable correlations with very similar *l* and *m* values. The mechanism of reactions of thiophosphinyl compounds such as 4-nitrophenyl phenyl thiophosphorochloridate (4-NO₂PhOP(S)(Cl)OPh, **1**) have been less studied, in spite of their importance as highly unstable substrates.³

In this work, we investigated the solvolyses of 4-nitrophenyl phenylthiophosphorochloridate (**1**) in pure solvents and mixed binary solvents to obtain exact kinetic information in various solvent systems as shown in equation (2). Particularly, we also investigated for the mechanistic difference owing to the change of the reaction substrates(**1** ~ **5**) of phosphoryl (P=O) or thiophosphoryl (P=S) and a phenyl or phenoxy group possessing P atom. In addition to the application of the extended Grunwald-Winstein equation to the specific rates, the influence of temperature on the specific rate in the three solvents has been discussed by calculated activation enthalpies and entropies. For understanding a further exact mechanistic informa-

tion, the kinetic solvent isotope effect (KSIE), the kinetic runs were performed in deuterated methanol (MeOD) and deuterated water (D₂O).



As further research of this series of work, we carried out kinetic studies of the solvolyses of 4-nitrophenyl phenyl thiophosphorochloridate (4-NO₂PhOP(S)(Cl)OPh, **1**), and the specific rates (first-order rate constants) are compared to those previously reported for the diphenyl thiophosphorochloridate ((PhO)₂PSCl, **2**),^{11c} diphenyl phosphorochloridate ((PhO)₂POCl, **3**),¹⁰ diphenyl phosphinic chloride (Ph₂POCl, **4**),^{11a} and diphenyl thiophosphinic chloride (Ph₂P(S)Cl, **5**).^{11b} Our purpose of this study is to draw a conclusion of an exact mechanism using the sensitivities, *l* and *m* obtained from the extended Grunwald-Winstein equation (1) compared to the previously reported solvolytic reactions for **2** ~ **5**. The presence of an electron-withdrawing ligand (4-NO₂PhO) in **1** is expected to lead the changes in the TS structure, which should be reflected in the magnitude of the *l* and *m* values. These solvolytic reactions could be influenced by the electronic interaction strongly between the reaction center (P) and the electron withdrawing substituent, 4-NO₂.



Results and Discussion

The specific rates of solvolysis of **1** were determined at 55.0 °C in 29 solvents. Used solvents are consisted of ethanol, methanol, and binary mixtures of water with ethanol, methanol, acetone, and 2,2,2-trifluoroethanol (TFE). The rate constants are reported in Table 1 together with *Y*_{Cl}¹ and *N*_T¹ values. In order to compare with the previously reported kinetic results, the specific rates, at 55.0 °C, for the corresponding solvolyses of diphenyl thiophosphorochloridate (**2**) are also reported in Table 1.

The specific rates for **1** are summarized in Table 2 after the rate are measured at the three concentrations changing 0.550, 1.021, 2.112 mol·L⁻¹ at 55.0 °C for pure ethanol and 50% ethanol. The specific rates of solvolysis of **1** were not found to depend on the initial concentrations of the substrate, as shown

Table 1. Specific rates of solvolysis of 4-nitrophenyl phenyl thiophosphorochloridate (4-NO₂PhOP(S)(Cl)OPh, **1**)^a in various pure and mixed solvents at 55.0 °C, the *N*_T and *Y*_{Cl} values for the solvents, and the corresponding specific rate values (*k*^b) for diphenyl thiophosphorochloridate ((PhO)₂PSCl, **2**).

Solvent ^b	10 ³ <i>k</i> ^c (s ⁻¹), 1	10 ³ <i>k</i> ^c (s ⁻¹), 2 ^d	<i>N</i> _T ^e	<i>Y</i> _{Cl} ^f
100% EtOH	0.955 ± 0.002	0.0585 ± 0.0007	0.37	-2.52
90% EtOH	3.31 ± 0.02	0.526 ± 0.003	0.16	-0.94
80% EtOH	8.91 ± 0.02	0.789 ± 0.007	0.0	0.0
70% EtOH	9.54 ± 0.03	1.10 ± 0.03	-0.20	0.78
60% EtOH	12.0 ± 0.2	1.64 ± 0.04	-0.38	1.38
50% EtOH	20.4 ± 0.2	2.41 ± 0.07	-0.58	2.02
40% EtOH	49.0 ± 0.5	4.58 ± 0.04	-0.74	2.75
20% EtOH	85.1 ± 0.7	10.2 ± 0.3	-1.16	4.09
100% MeOH ^g	1.91 ± 0.02	0.205 ± 0.004	0.17	-1.20
90% MeOH	4.90 ± 0.04	1.12 ± 0.03	-0.01	-0.20
80% MeOH	10.5 ± 0.2	2.18 ± 0.05	-0.06	0.67
70% MeOH	27.5 ± 0.3	2.75 ± 0.06	-0.40	1.46
60% MeOH	52.5 ± 0.4	4.26 ± 0.05	-0.54	2.07
50% MeOH	83.2 ± 0.7	7.25 ± 0.06	-0.75	2.70
40% MeOH	151 ± 3	11.6 ± 0.3	-0.87	3.25
20% MeOH	324 ± 7	19.7 ± 0.5	-1.23	4.10
95% Acetone	0.107 ± 0.002	0.00178 ± 0.00005	-0.49	-3.19
90% Acetone	0.240 ± 0.003	0.0204 ± 0.0004	-0.35	-2.39
80% Acetone	0.956 ± 0.006	0.141 ± 0.003	-0.37	-0.83
70% Acetone	2.95 ± 0.04	0.417 ± 0.006	-0.42	0.17
60% Acetone	13.8 ± 0.3	0.776 ± 0.008	-0.52	1.00
50% Acetone	36.3 ± 0.5	2.02 ± 0.05	-0.70	1.73
40% Acetone	52.5 ± 0.8	3.74 ± 0.07	-0.83	2.46
30% Acetone	95.4 ± 1.2	6.35 ± 0.07	-0.96	3.21
90% TFE ^h	0.0891 ± 0.0003		-1.11	3.77
80% TFE	0.363 ± 0.002	0.102 ± 0.003	-1.23	4.28
70% TFE	1.05 ± 0.02	0.154 ± 0.004	-1.98	2.96
50% TFE	5.25 ± 0.03	0.525 ± 0.003	-1.73	3.16
100% H ₂ O	108 ± 4	10.2 ± 0.3	-1.38	4.57

^aUnless otherwise indicated, a 10⁻³ M solution of the substrate in the indicated solvent, containing 0.1% CH₃CN. ^bOn a volume-volume content at 25.0 °C, other component is water. ^cWith associated standard deviations. ^dValues from ref. 11c. ^eValues from ref. 4a. ^fValues from ref. 3. ^gValues of *k* (= 7.93(± 0.04) · 10⁻⁴ s⁻¹) in methanol-*d* (MeOD), corresponding to *k*_{MeOH}:*k*_{MeOD} value of 2.41 ± 0.03 [with associated standard error (Crumpler, T. B.; Yoh, J. H. *Chemical Computations and Error*, Wiley: New York, 1940: p 178)]. ^hSolvent prepared on a weight-eight basis at 25.0 °C, other component is water.

in Table 2.

For three kinds of solvents, specific rates of solvolyses of **1** were measured at three additional temperatures (Table 3). The enthalpies and entropies of activation calculated using these values are also presented in Table 3.

In the present study, we are concerned with the specific rates of the solvolyses represented in equation (2). In most solvents, the reactions were proceeded fast, therefore we employed the conductivity measurements were followed to be able to record the responses to a function of time.¹² In order to promote a rapid dissolution in the solvent, the substrate was added as a small volume of a concentrated stock solution in acetonitrile such

Table 2. Specific rates of solvolyses of 4-nitrophenyl phenyl thiophosphorochloridate (**1**) in ethanol and ethanol-water with variation of the concentration of the substrate at 55.0 °C.

Solvent	1 , M ^a	10 ³ k ^b , s ⁻¹
100% EtOH	0.550	0.954 ± 0.003
	1.021	0.953 ± 0.002
	2.112	0.957 ± 0.002
80% EtOH	0.550	8.93 ± 0.03
	1.021	8.89 ± 0.03
	2.112	8.92 ± 0.02
50% EtOH	0.550	20.5 ± 0.2
	1.021	20.2 ± 0.3
	2.112	20.4 ± 0.2

^aConcentration of stock solution in CH₃CN. ^bThe k values are the averages of the result from at least three times kinetic runs, and with associated standard deviation.

Table 3. Specific rates and activation parameters for the solvolyses of 4-nitrophenyl phenyl thiophosphorochloridate (**1**)^a in pure and aqueous solvents at various temperatures.

Solvent	Temp. (°C)	10 ³ k ^b (s ⁻¹)	ΔH [‡] (kcal·mol ⁻¹) ^c	-ΔS [‡] (cal·mol ⁻¹ ·K ⁻¹) ^c
100% EtOH	25	0.194 ± 0.002	9.62 ± 0.17	44.9 ± 0.6
	35	0.330 ± 0.003		
	45	0.562 ± 0.004		
	55	0.955 ± 0.007		
80% EtOH ^d	25	1.42 ± 0.03	11.2 ± 0.1	34.1 ± 0.5
	35	2.65 ± 0.4		
	45	4.82 ± 0.4		
	55	8.91 ± 0.7		
100% MeOH	25	2.92 ± 0.02	11.9 ± 0.3	37.6 ± 0.7
	35	5.38 ± 0.03		
	45	1.02 ± 0.03		
	55	1.91 ± 0.04		

^aA 10⁻³ M solution of the substrate in the indicated solvent, also containing 0.1% CH₃CN. ^bAverages of three or more runs, with standard deviation. ^cThe activation parameters are accompanied by the standard error. ^dOn a volume-volume content at 25.0 °C, other component is water.

that the reaction solution contained about 0.1% acetonitrile.

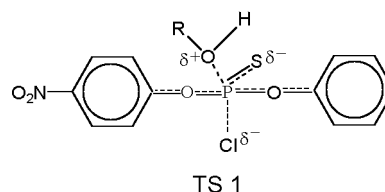
The specific rates were observed to increase with increasing water content for binary aqueous mixtures. The specific rates of ethanolysis of **1** were higher ($k = 9.55 \times 10^{-4} \text{ s}^{-1}$ at 55.0 °C) than that of ethanolysis of **2**^{9,10} ($k = 5.85 \times 10^{-5} \text{ s}^{-1}$ at 55.0 °C). This means that the solvents are contributed to make a tight bond in TS between the reaction center of phosphorus and the leaving group (Cl) and to develop the bond cleavage of the leaving group (Cl) a little high in the reaction of **1**, equation (2).

Comparing with the difference of electron withdrawing ability between nitro group and hydrogen group which are substituted at *para*-position of phenyl ring, the positive charge of the reaction center, P in **1** is much higher than that in **2**.

The rate for the solvolysis of **1** is much faster than that of **2** (Table 1). This is consistent with the substituent effect based on the electron withdrawing ability of the substrates. The rate of ethanolysis of **2** ($k = 5.85 \times 10^{-5} \text{ s}^{-1}$ at 55.0 °C) is lower than

that of ethanolysis of **3** ($k = 1.41 \times 10^{-4} \text{ s}^{-1}$ at 0.0 °C). It is indicated that the P=S group is much favored to be lowered the leaving ability of Cl than of the P=O group.

The specific rates change with substituents X (= H and 4-NO₂) in according to those expected from solvolyses reactions with negative charge development at the reaction center (P) in the TS. The specific rates of **1** (X = 4-NO₂) are faster than of **2** (X = H) at 55.0 °C. This is due to a greater positive charge on the P atom in **1** (TS 1) than in **2** by the electron-withdrawing effect of the 4-NO₂ substituent in **1**, which indicates of the importance of bond making in the rate-determining step.¹³



The phenoxy group ($\sigma_1 = 0.40$) has a stronger electron-withdrawing ability than the phenyl group ($\sigma_1 = 0.12$).¹⁴ Comparing with the difference of inductive effects between the phenoxy and the phenyl group, the positive charge of the reaction center P in **4** (and **5**) would be smaller than that in **1** (and **2** and **3**). The specific rate constants of ethanolysis of **2** are shown higher than that of **5** compared to the positive charge of the reaction center of P atom. On the contrary, the observed rate of **5** ($k = 1.20(\pm 0.02) \times 10^{-4} \text{ s}^{-1}$ in 100% EtOH at 25.0 °C) is faster than that of **2** ($k = 8.72(\pm 0.02) \times 10^{-6} \text{ s}^{-1}$ in 100% EtOH at 25.0 °C). This result imply that the reaction rate does not only depend on the positive charge of the reaction center P.

In the case of **5**, two phenyl groups are attached to the reaction center P atom, whereas oxygen atoms are intervened the interaction between the reaction center P and the phenyl group in **2**. As a result, the steric hindrance would be shown much larger in **5** than in **2** when the solvent nucleophiles attack the reaction center from the opposite of the leaving group, i.e., backside nucleophilic attack.^{2k}

Some phosphate systems are more reactive than their thiophosphate counterparts by two or more orders of magnitude.¹⁵ Phosphinate systems are generally less sensitive to S substitution in the P=O bond than phosphate systems: $k_{\text{P=O}}/k_{\text{P=S}} < 10$ for the alkaline hydrolysis in 60% DME-H₂O and H₂O in a series of alkyl phosphinates,¹⁶ and $k_{\text{P=O}}/k_{\text{P=S}} = 2.4 \sim 5.2$ for the hydrolyses of (CH₃)₂P(O)OPhX and (CH₃)₂P(S)OPhX.^{2j} Our results, the rate ratio of $k_{\text{P=O}}(\mathbf{2})/k_{\text{P=S}}(\mathbf{3}) (= 20$ at 55.0 °C) is also consistent with the reported works.¹⁵ The P=O systems are generally more reactive than their P=S counterparts for several reasons, including the so-called thio effect which is mainly the electronegativity difference between O and S which favors O over S.¹⁷

The activation parameters, ΔH[‡] and ΔS[‡], for solvolysis of **1** based on the specific rates at four temperatures in Table 3 are consistent with our proposed mechanism. The small positive ΔH[‡] values (= 9.62 ~ 11.9 kcal·mol⁻¹) and large negative ΔS[‡] values (= -34.1 ~ -44.9 cal·mol⁻¹·K⁻¹) are shown to be the

characteristics of a kind of the relatively late TS with a large degree of bond making and leaving group departure.¹⁸ The large negative values of ΔS^\ddagger are accord with the characteristics of a kind of relatively late TS with a large bond cleavage which is not require much energy in the case of a strong leaving group, Cl.^{21,k} The large negative ΔS^\ddagger values may result from both large degree of bond cleavage and a strong steric hindrance in the bond making of the solvent.

Halmann¹⁹ reported of the specific rate of ethanolysis of the

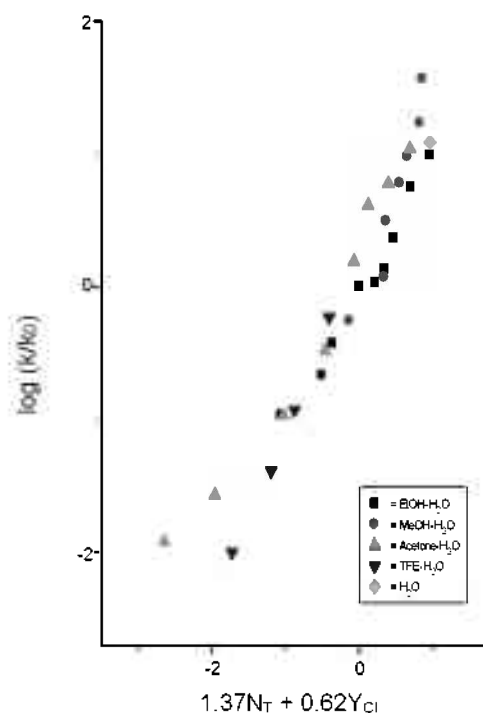


Figure 1. Plot of $\log(k/k_0)$ for the solvolyses of 4-nitrophenyl phenyl thiophosphorochloridate (**1**) at 55.0 °C against $(1.37N_T + 0.62Y_{Cl})$.

related diethylphosphinyl chloride, Et_2POCl , in the range of the concentration of 2.5×10^{-3} to 17×10^{-3} M. We found no perturbation of this tendency over a threefold variation at our lower concentrations ($0.5 \sim 2 \times 10^{-3}$ M) of **1** undergoing solvolyses in 100% ethanol, 80% or 50% ethanol as shown Table 2.

Calculated sensitivities obtained from the extended Grunwald-Winstein equation [eq. (1)]³⁻⁵ are shown as 1.37 ± 0.11 for l and 0.62 ± 0.04 for m in 29 solvents as shown in Table 1 and Figure 1 with a multiple correlation coefficient of 0.959. Sensitivity values, l and m are well correlated as shown in Table 4 compared with the other values reported for similar substrates.^{20,23}

Therefore, the determination of these values will be a valuable source of information concerning the structure of the transition state for these solvolyses.²¹ The l and m values for the solvolysis of **1** were compared with recently reported results as shown in Table 4 after analyzed in terms of equation (1) for the specific rates of solvolyses of diphenyl thiophosphorochloridate,^{9,10} diphenyl phosphinyl chloride,¹¹ isopropyl sulfonylchloride,⁸ *N,N*-dimethyl sulfamoylchloride,⁸ 2-phenyl-2-ketoethyl tosylate,²² dimethyl thiophosphorochloridate,⁷ and *N,N,N',N'*-tetramethyl dimidophosphorochloridate.⁶ The l value of 1.37 and the m value of 0.62 for the solvolysis of **1** were very similar to the previously reported values for the bimolecular solvolyses of other substrates (Table 4).^{6-8,22} which suggests an $\text{S}_{\text{N}}2$ mechanism involving an attack by the solvent at phosphorus atom of **1**. The solvolysis of **1**, where bond making ($l = 1.37$) is more progressed than bond breaking ($m = 0.62$), and the values are still in the range of $\text{S}_{\text{N}}2$ mechanism, reflecting on the degree of the nucleophilic assistance based on the measure of solvent nucleophile.^{23c}

For the solvolysis of **1**, the ratio of l/m value was calculated as 2.2 which is similar to those of *N,N*-dimethyl sulfamoyl chloride,²³ 2-phenyl-2-ketoethyl-tosylate,²² dimethyl thiophos-

Table 4. Extended Grunwald-Winstein correlations of the specific rates of solvolyses of solvolytic displacements of chloride from phosphorus.

Substrate	n^a	l^b	m^b	R^c	l/m
4-NO ₂ PhOP(S)(Cl)OPh	29	1.37 ± 0.11	0.62 ± 0.04	0.959	2.2
(PhO) ₂ PSCl ^{11c}	27	1.12 ± 0.11	0.61 ± 0.02	0.990	1.8
Ph ₂ PSCl ^d	29	1.03 ± 0.08	0.66 ± 0.05	0.933	1.6
Ph ₂ PSCl ^e	25	1.00 ± 0.04	0.64 ± 0.03	0.983	1.6
Ph ₂ POCl ^f	31	1.44 ± 0.13	0.58 ± 0.09	0.920	2.5
Ph ₂ POCl ^g	27	1.42 ± 0.10	0.54 ± 0.07	0.956	2.6
Ph ₂ PCl ^h	29	1.31 ± 0.14	0.51 ± 0.09	0.899	2.6
Ph ₂ PCl ⁱ	25	1.25 ± 0.09	0.46 ± 0.06	0.954	2.7
(MeO) ₂ POCl ^h	22	1.36 ± 0.23	0.54 ± 0.13	0.844	2.5
(MeO) ₂ POCl ^{e,h}	18	1.24 ± 0.14	0.45 ± 0.08	0.941	2.8
(MeO) ₂ PSCl ^h	31	1.21 ± 0.10	0.60 ± 0.04	0.943	2.0
(MeO) ₂ PSCl ^{e,h}	28	1.16 ± 0.08	0.55 ± 0.03	0.966	2.1
(Me ₂ N) ₂ POCl ⁱ	31	1.20 ± 0.07	0.69 ± 0.04	0.958	1.7
(Me ₂ N) ₂ POCl ^{e,i}	27	1.14 ± 0.05	0.63 ± 0.03	0.982	1.6
(PhO) ₂ POCl ^j	29	1.31 ± 0.10	0.61 ± 0.04	0.960	2.1

^aNumber of solvents. ^bFrom eq. (1) and with associated standard error. ^cMultiple correlation coefficient. ^dFrom ref. 11b. ^eWith the TFE-EtOH data points excluded from the correlation. ^fFrom ref. 11a. ^gFrom ref. 26. ^hFrom ref. 7. ⁱFrom ref. 7. ^jFrom ref. 10.

phorochloridate,⁷ and *N,N,N',N'*-tetramethyldiamido-phosphorochloridate⁸ to suggest the S_N2 mechanism.

We found that the use of *N_T* values in conjunction with *Y_{Cl}* values led to acceptable correlations, with similar *l* and *m* values compared with those obtained in the analyses of the specific rates of solvolyses for other entries in Table 4. The only difference is smaller *l* value for the solvolysis of **1**, possibly reflecting a decreased nucleophilic participation at the TS due to reduced electronegativity of the P=S compared to the P=O.

In methanol and methanol-*d* (MeOD), a KSIE (*k_{MeOH}*/*k_{MeOD}*) of 2.41 ± 0.03 at 55.0 °C is observed (*k_{MeOD}* = 7.93 (± 0.04) × 10⁻⁴ s⁻¹). This result is in the range 1.58 ± 0.05 to 2.31 ± 0.07 which were observed²⁴ for the corresponding methanolyses of a series of benzenesulfonyl chlorides at 25.0 °C, in which the reactions were believed to be S_N2 in character. The methanolyses of meta- and para-chlorobenzyl chloride and para-nitrobenzyl chloride, believed to be S_N2 in character, also showed values in the range from 1.49 ± 0.05 to 1.89 ± 0.07.²⁵ Reported values have indicated that values in these ranges can be considered as good supporting evidence for the postulation of an S_N2 mechanism for a methanolysis. In water (H₂O) and deuterated water (D₂O), a KSIE of 2.57 ± 0.06 at 55.0 °C is also observed (*k_{D2O}* = 4.20(± 0.02) × 10⁻² s⁻¹). On the basis of the observed KISE value, the possibility of a S_N1 mechanism for the hydrolysis of **1** could be excluded.^{24,25}

In summary, the solvolyses of 4-nitrophenyl phenyl thiophosphorochloridate (**1**) in ethanol, methanol, and aqueous binary mixture incorporating ethanol, methanol, acetone, and TFE at 55.0 °C are proceed with a concerted S_N2 process with a late TS. The result was drawn on the base: (1) similar sensitivities (*l* = 1.31 and *m* = 0.62) with those obtained for diphenyl thiophosphorochloridate (**2**), diphenyl phosphorochloridate (**3**), diphenyl phosphinic chloride (**4**), and diphenyl thiophosphinic chloride (**5**); (2) the large kinetic solvent isotope effects (= 2.41 in MeOH/MeOD and 2.57 in H₂O/D₂O); and (3) small Δ*H*[‡] with large negative Δ*S*[‡] values.

Experimental

Solvents were purified as previously described.²⁵ The substrate did not react with the pure acetonitrile within the stock solution. 4-Nitrophenyl phenyl thiophosphorochloridate (**1**) was prepared by reacting phenyl phosphorodichloridothionate with 4-nitro-phenol. The phenyl phosphorodichloridothionate (Aldrich 98%) was used as received. A solution of phenyl phosphorodichloridothionate 0.01 mol in 15 mL of HPLC grade acetonitrile was added to a solution of required amount of 4-nitro-phenol for 0.01 mol and 0.01 mol of triethylamine in 15 mL of the same acetonitrile on an ice bath. The solution was stirred on an ice bath for 2 hours. Triethylamine hydrochloride salt was separated by filtration. Acetonitrile was evaporated under reduced pressure. The remaining product was treated with ether and water for work-up, and 5% NaHCO₃ solution was treated to remove excess 4-nitrophenol. After work-up, anhydrous MgSO₄ was added, kept 4 hours, and the solvent was removed under reduced pressure by using the rotary evaporator after removing MgSO₄ by filtration.

Finally, the product was passed through column chromatography (ethyl acetate + n-hexane) for purification. (NO₂C₆H₄OP(S)(Cl)OC₆H₅): Liquid. Calc. for C₁₂H₉O₄PSNCl: C, 43.72; H, 2.75. Found: C, 43.69; H, 2.79%. ¹H-NMR, δ_H(CDCl₃) 6.6 - 8.1(OC₆H₅-H + OC₆H₄NO₂-H, 9H, m), *m/z* 329(M⁺).

The kinetic experiments were carried out by allowing a conductivity cell containing 12.5 mL of solvent to equilibrate, with stirring, in a constant-temperature water bath. A 12 μL portion of a 1.0 mol dm⁻³ stock solution of **1** in acetonitrile was then added. The monitoring of increases in conductivity with time and the calculation of the specific rates (first-order coefficients) were conducted as previously reported.¹¹ The multiple regression analyses were performed using commercially available packages.

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