American Journal of Organic Chemistry 2015, 5(3): 83-94
DOI: 10.5923/j.ajoc.20150503.01

A Review on Nucleophilic Substitution Reactions at P=O Substrates of Organophosphorous Compounds

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Abstract Nucleophilic substitution reactions at P=O substrates of organophosphorous compounds are very much important in organic chemistry. The problems of the mechanism of displacement at phosphorous have continued to be challenging ones. Physical organic chemistry tools; Hammett (ρ), Brönsted (β) LFER, CICs and heavy atom KIE have been used in quest for the mechanistic information. Two main types of displacement processes are well known in neutralphosphoryl group transfer reactions: concerted involving displacementat phosphorus through a single pentacoordinate transition state (TS) and stepwise mechanism involving a trigonal bipyramidal pentacoordinate (TBP-5C) intermediate. In some cases mechanistic change from concerted to stepwise or *vice versa* have been observed. In this article an attempt is made to provide an overview of the mechanistic understanding of substitution reaction at P=O substrates of organophosphorous compounds.

Keywords Phosphoryl transfer reaction, Concerted mechanism, Transition state, TBP-5C intermediate, Front side attack, Backside attack, Aminolysis, Pyridinolysis

1. Introduction

Nucleophilic substitution reactions are an important class of reactions that allow the interconversion of functional groups which are ubiquitous in organic chemistry. This holds, in particular for nucleophilic substitution at carbon centers, which is known forever 100 years [1]-has been the subject of many experimental and theoretical studies. There is much current interest to study nucleophilic substitution reactions at phosphorous in solutions and understanding the kinetics and mechanism. Phosphorous compounds are useful in multipurpose [2]. These compounds can be used as agricultural chemicals like pesticides, medicinal compounds, flame reterdants for fabrics and plastics, plasticizing and stabilizing agents in the plastic industries, oil and gasoline additives and corrosion inhibitors.

There are two fundamental events in these substitution reactions: formation of new bond to the nucleophile and breaking of the bond to the leaving group. The nucleophilic substitution at neutral phosphoryl species have been considered to proceed either stepwise through a trigonal bipyramidal pentacoordinate (TBP-5C) intermediate (Upper route) or concertedly through a single pentacoordinate transition state(TS) (Lower route) in scheme 1 where the attacking and leaving groups occupy apical positions, i.e. backside nucleophilic attack toward the leaving group [3].

Tetracoordinated organophosphorous compounds were synthesized, characterized and nucleophilic substitution reactions were investigated by varying substituents around phosphorous center or in a nucleophile using different methods like conductometric method and spectrophotometric method. All of the classically used tools of Physical Organic Chemistry like Hammett and Brönsted linear free energy relationship(LFER) [4], cross interaction constants (CICs) [5], heavy atom(deuterium) kinetic isotope effects(KIEs) [6], activation enthalpy and activation entropy have been used to interpret mechanistic understanding of phosphoryl group transfer reactions.

The very recent studies showed that in case of concerted mechanism the nucleophile can approach towards reaction center in two different ways: A hydrogen bonded, four-centre type TS is suggested for a front side attack while TBO-5C TS is suggested for a backside attack based on the deuterium kinetic isotope effects [7] as shown in scheme 2.

There has been continuous interest in phosphoryl transfer and related reactions due to environmental significance as well as biological importance [2, 8]. In this article an attempt is made to provide an overview of the reaction mechanism at phosphorous center and mechanistic understanding of the phosphoryl transfer reaction. The literature survey covers articles appearing up to May 2014.

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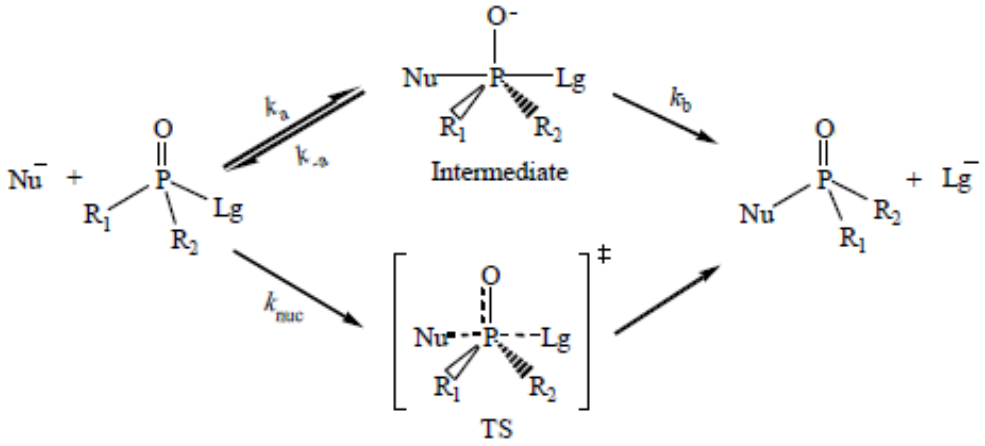
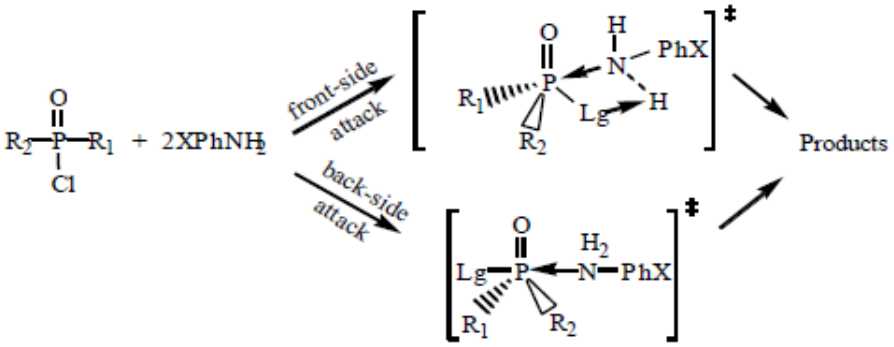


Scheme 1. Schematic representation on nucleophilic substitution at P center on phosphoryl group transfer reaction



Scheme 2. Schematic representation of nucleophilic attack on P center in concerted mechanism

2. Mechanistic Tools

In the early part of twentieth century the quantitative study of LFER was introduced by the Danish scientist Johannes Nicolaus Brönsted (1923) and Swedish scientist Louis Plack Hammett (1937).

2.1. The Hammett Equation [4, 9, 31]

It shows a linear correlation between $\log(k_x/k_H)$ of meta- and para substituted phenyl derivatives and corresponding substituent constants in case of benzoic acid ionaization in aqueous medium at 25°C. The Hammett equation is expressed as,

$$\log(k_X/k_H) = \rho\sigma \quad (1)$$

or, $\log k_X = \rho\sigma + \log k_H$

where σ is the substituent constant and ρ is the reaction constant or Hammett coefficients obtained by plotting log k_2 vs. σ_X.

2.1.1. Significance of Sign and Magnitude of ρ

The susceptibility of the reaction to substituents, (+ve) sign; a reaction favored by EWS and ρ <1 indicates negative charge is built, (−ve) sign and ρ > 1 suggest reverse situation.

2.2. The Brönsted Equation [10, 11]

The Gibbs free energy for proton dissociation is proportional to the activation energy (equation 2) for the catalytic step. When the relationship is not linear, the chosen group of catalysts do not operate through the same reaction mechanism.

$$k_b = G_b K_b^{\beta} = G_b (K_W/K_a)^{\beta} = G_b K_a^{-\beta} \quad (2)$$

or $\log kb = \beta pK_a + \text{Constant}$

The Brönsted correlations of rate constants with nucleophile pK_a (β_X) is one measure of the degree of nucleophile bond formation in the rate determining TS. Reactions that have low values for proportionality constants (β_X) are considered to have a transition state closely resembling the reactant with little proton transfer, with a high value, resembles product.

2.3. Kinetic Isotope Effects (KIEs) [6]

The term k_H/k_D is known as kinetic isotope effects. It provides mechanistic information. Isotopic substitution does not affect the potential energy surface of the molecule nor does it perturb the electronic energy levels. It is only those properties that are dependent upon atomic masses which are unaffected; for chemical purposes, the perturbation can be

considered to be limited to vibrational frequencies. The following types of isotope effect are distinguished:

(a) primary kinetic isotope effect (PKIE): in which the bond to the isotopic atom is broken in the rate determining step, $k_H/k_D >> 1$;

(b) secondary kinetic isotope effect (SKIE), in which the bond to the isotopic atom (s) remains intact throughout the reaction, $k_H/k_D << 1$ or k_H/k_D, around, 1;

(c) solvent isotopic effects, which result from isotopic differences in the medium, e.g., if the solvent is changed from H_2O to D_2O, then $k(H_2O) / k(D_2O)$ is obtained as solvent isotope effect.

More precisely The net KIE of less than unity, (k_H/k_D)net < 1, implies the secondary inverse

KIE while the net KIE of greater than unity, (k_H/k_D)net> 1, implies a primary KIE. The primary KIE suggests that partial deprotonation of nucleophile occurs by hydrogen bonding in the rate determining step retaining the configuration whereas The secondary inverse KIE is ascribed to the increment of out-of-plane bending vibrational frequencies of C−H(D) bonds in the TS because of steric congestion of the hydrogen (deuterium) atom in the C−H(D) moiety in the bond-making step and inversion of configuration is found.

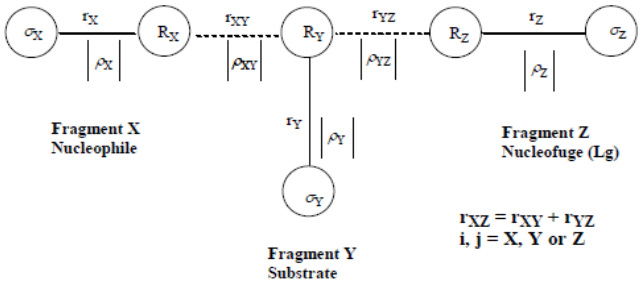
2.4. Cross-Interaction Constants Theory [5]

2.4.1. Definition

The multiple substituents effect can also be analyzed quantitatively by extending these classical equations to include second derivative parameter, termed as Cross-interaction constants (CICs), shown in equation 3 and 4. It has become a very useful concept in the study of reaction mechanism. The CICs, ρ_{ij} (ρ_{XY}, ρ_{YZ}, ρ_{XZ}), Hammett type constant and β_{ij}(β_{XY}, β_{YZ}, β_{XZ}), Brönsted type constant represent the intensity of interaction between the two interacting molecules i (e.g., a nucleophile) and j (an electrophile) in the adduct (Scheme 3)

$$\log (k_{ij}/k_{HH}) = \rho_i\sigma_i+\rho_j\sigma_j+\rho_{ij}\sigma_i\sigma_j \quad (3)$$

$$\log (k_{ij}/k_{HH}) = \beta ipK_{a(i)}+\beta_j pKa_{(j)}+\beta_{ij}\ pK_{a(i)}\ pKa_{(j)} \quad (4)$$



Scheme 3. Typical S_N2 TS

2.4.2. Significances

Lee and coworkers [12, 7c] have been developing Cross-interaction constant theory for the last twenty five years. Significances of Cross-interaction constants have been described based on sign and magnitude.

Table 1. Summarization of significance of the sign and magnitude of the CICs in explaining quantitative mechanistic criteria

Mechanism	Sign
S_N1	
Concerted S_N2	ρXY = 0, ρYZ > 0, ρXZ = 0
Addition-Elimination	ρXY < 0, ρYZ > 0, ρXZ >0 or ρXZ < 0
formation of $T^{\pm}$	ρXY < 0, ρYZ ≡ 0, ρXZ >0 or ρXZ < 0
breakdown of $T^{\pm}$	ρXY > 0 , ρYZ < 0, ρXZ > 0

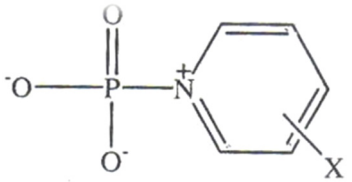
The magnitudes of the cross-interaction constants are indicative of a measure of the transition state structure. The magnitude of ρ_{ij} is related inversely to the distance between the two substituents rij, since the interaction will be stronger, at a shorter distance. On the other hand, the magnitude of Bronsted type constants, β_{ij}, represents the intensity of direct interaction between the two reaction centers Ri and Rj. It should be noted that there are two types of extreme cases, the cross-interaction constant nearly vanishes, i.e. $[\rho_{ij}] \approx 0$ and $[\beta_{ij}] \approx 0$ or the magnitude is abnormally large.

3. Results and Discussion

Many researchers have been carried out on phosphoryl transfer reactions of organophosphorous compounds in solution. One of the most confusing issues in the mechanistic understanding is whether phosphoryl transfer reactions in solution are concerted process or whether they proceed through stepwise. Here the author tries to analyze the reported results.

3.1. Concerted Nucleophilic Substitution Reactions at P=O

Reactions following concerted mechanism proceed through the formation of single transition state, i.e. bond formation and bond breaking occur simultaneously in transition state.



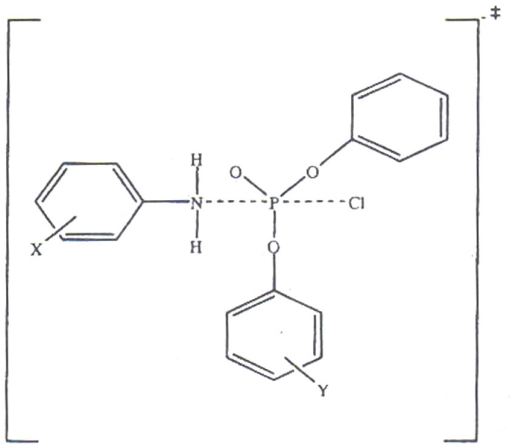
I

Jencks et al. (1984) [3i] and Williams et al. (1984) [13] reported the pyridinolysis of phosphoryl pyridinium compounds, **I**, and showed that most likely mechanism is a concerted substitution reaction with an "exploded" TS with weak bonds to the attacking and leaving groups. Jencks et al. [13] reported $\beta_X(\beta_{nuc})$ (0.17 and 0.19) for reactions of pyridines and primary amines with phosphorylated 3-methoxypyridine and reported β_X (β_{nuc}) (0.22 and 0.28) for

reactions of pyridines and primary amines with phosphorylated 4-morpholinopyridine. These low values are consistent with concerted mechanism.

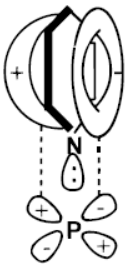
Williams et al. (1988) [14] have performed reactions of 4-nitrophenyl diphenyl phosphinate with aryl oxides in aq. medium and concluded that the reactions proceed through a concerted mechanism. The evidence suggested for a concerted mechanism is a linear Brönsted type plot for the reactions with a series of aryloxides whose pK_a values are greater than and less than that of the leaving 4-nitrophenoxide.

Guha et al. (1999) [12d] investigated the mechanism of aminolysis of phenyl substituted phenyl chlorophosphate with anilines in acetonitrile and the reported mechanism is concerted with late product like TS in which bond making and leaving group departure are extensive. The reaction mechanism has been described based on Hammett reaction constants, ρ_X(−3.4- −4.6), Brönsted coefficients, β_X (1.2 - 1.7) and large negative cross-interaction constant, ρ_{XY}(−1.31). The inverse secondary kinetic isotope effects, k_H/ k_D (o.61 – 0.87) are much lower than unity suggesting the following associative type transition state, **II**.



II

In a consequence Guha et al. (2000) [15] reported the mechanism of pyridinolysis of same substrate, phenyl substituted phenyl chlorophosphate in acetonitrile at 25°C as concerted with an early TS in which the extent of both bond formation and leaving group departure is small. The pyridinolysis rates are much faster than the corresponding rates for the aminolysis with isobasic anilines due to the resonance stabilization of p_π-$d_\pi$overlap between the π-orbital of the pyridine ring and the empty d-orbital of the phosphorus atom in the TS as suggested by Dewar [16]. This type of π-complex is not possible with aniline nucleophiles because the lone pair on the amino nitrogen is a p-type so that the horizontal π-cloud of the ring overlaps with the d-orbital of P marginally. Furthermore, since the attacking and leaving groups occupy apical positions of the trigonal bipyramidal (TBP) structure of a pentacoordinate TS or intermediate, the horizontal approach of the aniline ringshould cause excessive steric hindrance in contrast to a much less steric effect in the vertical approach of the pyridine ring, **III**.



III

A similar but much smaller rate ratio was noted in the aminolysis of phosphorylpyridinium compounds; for nucleophiles of p*K*a = 5, pyridines were 16-fold more reactive than primary amines with the same leaving group [3i]. Lee et al. (2002) [17] performed the reactions of para-chlorophenyl aryl chlorophosphates with anilines in acetonitrile at 55°C and the proposed mechanism is concerted based on negative cross-interaction constant ρ_{XY}(−0.31). The faster rates are observed than corresponding reactions with phenyl substituted phenyl chlorophosphate because of positive charge on the P atom due to strong electron-withdrawing effect of the p-Cl substituent in the phenolate group which is bonded to phosphorous.

Lee et al. (2000) [18] also reported theoretically the concerted nature of phosphoryl transfer reactions with Nu = LG = Cl-. The proposed structure of TS show that the attacking Cl^- and the leaving group Cl^- occupy the apical positions TBP-5C TS.

Um et al.(2006) [19] studied the aminolysis of aryl diphenyl phosphinates with alicyclic 2^o amine and suggested the mechanism as concerted with an early TS in which nucleophilic attack and leaving group departure are advanced only to a small extentat the TS on the basis of linear Brönsted type plot with small β_{nuc} (0.38) and small r values (0.30).

Hoque et al (2007) [20] performed the aminolysis of etyl Y-phenyl chlorophosphates with X-anilines in acetonitrile at 55°C kinetically and theoretically. The reported mechanism is concerted involving a partial front side attack through a hydrogen bonded four center type TS based on negative cross-interaction constant ρ_{XY} = −0.60. The large ρ_X (ρ_{nuc} = −3.1 to −3.4) and β_X (β_{nuc} = 1.1–1.2) values seem to be characteristic of the anilinolysis of phosphates [12d] with the Cl leaving group. Because of the relatively large size of the aniline nucleophile, the degree of steric hindrance could be the decisive factor that determines the direction of the nucleophilic attack to the phosphate substrates with the relatively small-sized Cl leaving group.

Um et al. (2009) [21] extended the kinetic study of aryl diphenyl phosphinates with eight different 1^o amine to investigate effects of amine nature on reactivity and reaction mechanism.

The Brönsted-type plot for the reactions of 2,4-dinitrophenyl diphenylphosphinate with primary amines is linear with β_{nuc} = 0.53. The reactions of with ethylamine also result in a linear Brønsted-type plot with β_{lg} = -0.81. These β_{nuc} and β_{lg} values are slightly larger than those reported previously [8] for the reactions of same substrate with secondary amines (β_{nuc} = 0.38) but typical for reactions that proceed through a concerted mechanism. It has been concluded that aminolysis of aryl diphenyl phosphinates proceed through a concerted mechanism and the nature of amines does not affect the reaction mechanism. However, the reactions with primary amines have been suggested to proceed through a later transition state (i.e., more bond formation and bond rupture in the transition state) on the basis of the larger β_{nuc} and β_{lg} values. The concerted mechanism has been further supported from the fact that the Yukawa-Tsuno plot for the reactions of aryl diphenyl phosphinate with ethylamine exhibits an excellent linear correlation with ρ = 2.24 and r = 0.22.

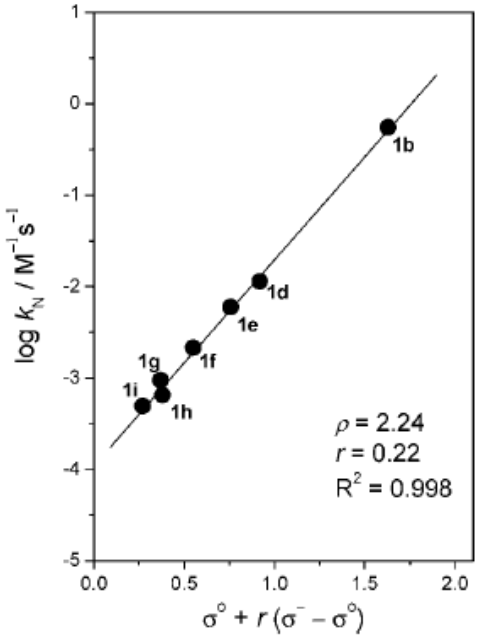
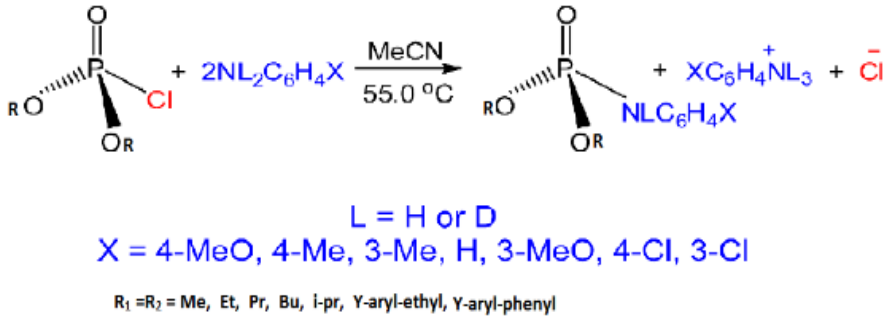


Figure 1. Yukawa-Tsuno plot for reactions of X-substituted phenyl diphenylphosphinates (**1b** and **1d-i**) with ethylamine in 80 mol % H2O/20 mol % DMSO at 25.0°C

Ethylamine (1° amine) is ca. 2-fold more reactive than piperidine (2° amine) toward 2,4-dinitrophenyl diphenylphosphinate, although the former is 0.35 p*K*a units less basic than the latter, indicating that solvation effect is not the only factor to govern the reactivity of primary and secondary amines. The nature of TS structure (early or late) are also an important factor to influence the reactivity order [21].

Lee et al. (2008, 2011, 2012) [22] studied the aminolysis of (R_1O) (R_2O) P(=O) type chlorophosphates (Eq. 5) in acetonitrile at 55°C by varying R_1 and R_2 to clarify the phosphoryl transfer.

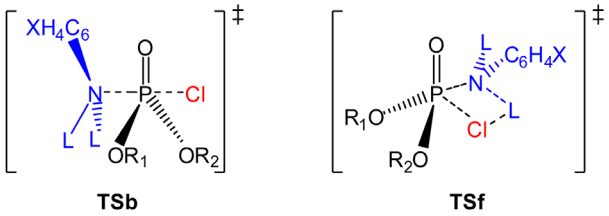


(5)

mechanism as well as to investigate the steric effects of the two ligands on the anilinilysis rates of the chlorophosphates by means of Taft's Eq.(6)

$$\log K_H = \delta \sum E_s + C \quad (6)$$

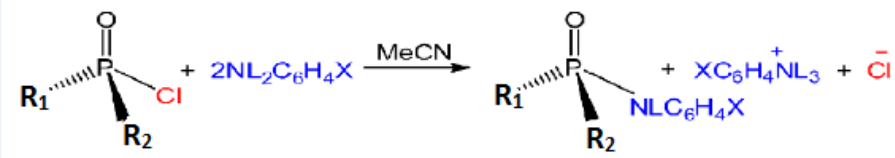
The Taft's Eq. (6) can be used to rationalize the steric effects of the two ligands on the reaction rate where k_H is the second-order rate constant with $C_6H_5NH_2$, ES is the Taft's steric constant [E_S(R) = 0(Me); –0.07(Et); –0.36(Pr); –0.39(Bu); –0.47(i-Pr); –2.48(Ph)], ΣE_S is the summation of the steric constants of the two ligands, and δ is the sensitivity coefficient [23]. From the plot of $\log K_H$ vs. $\sum E_s$ It was found that the substrate with two i-PrO ligands shows great negative deviation from the slope. is attributed to an unexpected steric hindrance of the two i-PrO ligands which cannot be predicted by the Taft's ΣE_S. It isevident that the anilinolysis rates of chlorophosphate systems are predominantly dependent upon the steric effects over the inductive effects of the two ligands. The anilinolysis rate is inversely proportional to the size of the two ligands; the larger the two ligands, the anilinolysis rate becomes slower. The authors proposed a concerted S_N2 mechanism for both strongly and weakly basic anilines regardless of the DKIEs, primary normal or secondary inverse but the attacking direction of aniline nucleophile can be semiquantitatively divided into three groups on the basis of the magnitudes of the k_H/k_D values: (i) predominant backside attack TS_b (Scheme 4) when $k_H/k_D < 1$; (ii) the fraction of the frontside attack involving a hydrogen-bonded fourcenter- type TS_f (Scheme 4) is greater than that of backside attack TS_b when $1.0 < k_H/k_D < 1.1$: (iii) predominant frontside attack TS_f when $k_H/k_D > 1.1$. In case of above mentioned reaction system the attacking direction of the anilinegradually changes from a frontside involving a hydrogen-bonded fourcenter-type TS_f with the strongly basic anilines to a backside with the weakly basic anilines.



Scheme 4. Backside attack TSb and frontside attack TSf

Lee et al. (2012) [24] also reported a concerted mechanism with both frontside TS_f and backside attacks TS_b and the fraction of a frontside attack is somewhat greater than that of backside attack for the pyridinolysis dibutyl chlorophosphate in acetonitrile on the basis of the magnitude of β_X (0.80) value.

Continuing the studies on phosphoryl transfer reactions, Lee et. al (2007, 2009, 2010, 2011) [25] further investigated the aminolysis of $R_1R_2P(=O)Cl$ type chlorophosphinates (Eq. 7) in MeCN by varying R_1 and R_2 to gain further information into the phosphoryl transfer reactions mechanism as well as to study the influence of steric effect of two ligands on reactivity and nucleophilic attack.



(7)

L = H or D

X = 4-MeO, 4-Me, 3-Me, H, 3-MeO, 4-Cl, 3-Cl

R_1, R_2 = Me,Me (1); Et, Et(2); Ph,Me(5); ph, ph(4); $cHex_2$, $cHex_2$(3)

The second-order rate constants, selectivity parameters (ρ_X and β_X), DKIE, ∑Es are given in Table 2.

Table 2. Summary of second-order rate Constants ($k_H \times 10^3/M^{-1}s^{-1}$) with $C_6H_5NH_2$ at 55.0 °C, summations of the Taft's steric Constants ($\sum E_s$) and Charton's corrected atomic Radii ($\sum v_X$), NBO Charges at the P reaction center, summations of the inductive effects ($\sum\sigma$), Brönsted coefficients (β_X), and DKIEs (k_H/k_D) of the reactions of **1, 2, 3, 4** and **5** with $XC_6H_4NH_2(D_2)$ in MeCN

Substrate	$k_H \times 10^3$	$-\sum E_S$	$\sum v_X$	Charges at P	$\sum\sigma_1$	$\beta_{X(H)}/\beta_{X(D)}$ [d]	k_H/k_D	Ref
1; $Me_2P(=O)Cl$	7,820[a]	0.00	1.04	1.793	−0.02	1.62/1.56[e]	0.740-0.945[e]	**[25a]**
2; $Et_2P(=O)Cl$	189[b]	0.14	1.08	1.817	−0.02	0.56/0.52[f]	0.828-0.974[f]	**[25b]**
3; $cHex_2P(=O)Cl$	0.00940[c]	1.58	1.74	1.863	0.00	0.67/0.56[g]	0.673-1.10[g]	**[25d]**
4; MePhP(=O)Cl	138	2.48	2.18	1.821	0.11	0.88/0.81[h]	1.62-2.10[h]	**[25a]**
5; $Ph_2P(=O)Cl$	1.73	4.96	3.32	1.844	0.24	1.69/1.62[h]	1.42-1.82[h]	**[25c]**

[a]The value of $k_H = 7{,}820 \times 10^{-3}$ $M^{-1}S^{-1}$ at 55°C was obtained by extrapolation in the Arrhenius plot (r = 0.999) with kinetic data: k_H = 776, 1010 and 1,610 × 10^{-3} M^{-1} S^{-1} at 0.0, 5.0 and 15.0°C, respectively, from ref. 25a. [b]The value of $k_H = 189\times10\text{-}3$ $M^{-1}S^{-1}$ at 55°C was obtained by extrapolation in the Arrhenius plot (r = 0.999) with kinetic data: k_H = 117, 162, and 211 ×10−3 $M^{-1}S^{-1}$ at 40.0, 50.0 and 60.0 °C, respectively, from ref. 25b. [c]Empirical kinetic value. [d] $\beta_{X(H)}/\beta_{X(D}$ indicates that the values are calculated from k_H and k_D values, respectively. [e]Values at 15.0°C. [f]Values at 50.0°C. [g]Values at 60.0°C. [h]Values at 55.0°C.

The observed sequence of the rate, **1**>>**2**>**4**>>**5**>>**3**, is completely contrary to expectations for the electronic influence of the two ligands. It is evident that the sequence of the anilinolysis rates of the phosphinicchlorides, **1** >**2** >**4**>**5**, is inversely proportional to the sizesof the two ligands; Ph, Ph (**5**) > Ph, Me (**4**) > Et, Et (**2**) > Me, Me (**1**). Thus the degree of steric hindrance is the major factor that determines both the reactivity of the phosphinates and the direction of the nucleophilic attack on the phosphinates. However, the anilinolysis rate of **3** exhibits exceptionally great negative deviation from the slope of $\delta = 0.737$ and $\nu = -1.60$. The authors tentatively suggest that the exceptionally slow rate of the anilinolysis of **3** is attributed to an unexpected steric hindrance of the two cyclohexyl ligands which cannot be predicted by the Taft's ΣE_S.

The DKIEs have provided a useful means to determine the TS structures in nucleophilic substitution reactions, and how the reactants, especially through changes in substituents, alter the TS structures. The DKIEs of five phosphinic chlorides change from secondary inverse with **1** (k_H/k_D = 0.740-0.945) [25a] and **2** (k_H/k_D = 0.828-0.974), [25b] via both secondary inverse and primarynormal with **3** (k_H/k_D = 0.673-1.10) [25d], to primary normal with **4** (k_H/k_D = 1.62-2.10) [25a] and **5** (k_H/k_D = 1.42-1.82) [25c] as the size of the two ligands becomes greater. All five substrates following concerted mechanism with the variation of direction of nucleophilic attack.

A Predominant backside nucleophilic attack is proposed for the anilinolysis of **1&2** while frontside attack via a hydrogen-bonded four-center-type transition state is proposed for the anilinolysis of **4 & 5**. However in case of **3**the obtained DKIEs imply that the fraction of a frontside attack increases as the aniline becomes more basic. A hydrogen-bonded, four-center-type transition state is suggested for a frontside attack, while the trigonal bipyramidal pentacoordinate transition state is suggested for a backside attack like before.

Um et al. (2013) [26] have investigated the alkaline hydrolysis of Y-Substituted-Phenyl

Diphenylphosphinates spectrophotometrically. The Brönsted-type plot for the reactions with OH– is linear with $\beta_{lg} = -0.36$. The Hammett plot correlated with σ– constants results in a slightly better correlation than that correlated with σo constants but exhibits many scattered points. In contrast, the Yukawa-Tsuno plot for the same reactions exhibits an excellent linear correlation with $\rho = 0.95$ and $r = 0.55$. The r value of 0.55 implies that a negative charge develops partially on the O atom of the leaving group. Thus, the reactions of Y-Substituted-Phenyl Diphenylphosphinates with OH– have been concluded to proceed through a concerted mechanism.

Barai et. al (2013) [27] reported a concerted S_N2 mechanism for the anilinolysis of bis(2-oxo-3-oxazolidinyl) phosphinic chloride in acetonitrile based on the selectivity parameters and activation parameters, the Brönsted coefficient of $\beta_X(H) = 1.14$ and the activation parameters ($\Delta H^{\ddagger} = 9.7$ kcal mol^{-1} and $\Delta S^{\ddagger} = -44$ cal mol^{-1} K^{-1}). The deuterium kinetic isotope effects (k_H/k_D) invariably increase from secondary inverse to primary normal as the aniline becomes more basic, rationalized by the transition state variation froma backside to a frontside attack.

3.2. Stepwise Nucleophilic Substitution Reactions at P=O

Nucleophilic substitution reactions at phosphorous center may also proceed through stepwise mechanism at P=O center.

Cook et al. (1986) have concluded that aminolysis of aryldiphenyl phosphinates and related compounds in MeCN proceed through a zwitterionic pentacoordinate intermediate with its breakdown being the RDS from studies of leaving group effects, solvent effects and activation parameters [28]. On the other hand, alkaline hydrolysis of aryl diphenyl phosphinates has been suggested to proceed through a pentacoordinate intermediate with its formation being the rate-determining step (RDS) on the basis of good Hammett correlations with $\acute{o}^{o}$ constants [29]. A similar conclusion has been drawn for imidazole catalyzed hydrolysis of aryl diphenylphosphinates by Willams et al. (1971) [30a] and alkaline ethanolysis of aryl dimethylphosphinates by Buncel et al. (2004). [30b]. Harger (2001) [30a] reported that the reaction between diphenylmethylphosphonamidic chloride and dialkyl amine proceeds through an elimination addition (EA) mechanism. In the course of the reaction phosphene intermediate was formed because the acidity of the C_α-H bond was greatly increased by the nitro group [3a]. Nome et al. (2003) reported a stepwise mechanism through intermediate formation for the reactions between bis (2, 4-dinitrophenyl) phosphates (BDNPP) with hydroxyl amine in water at 25°C [31].

Lee et al. (2011) [32] have studied the anilinolyses $(RO)_1$-$(RO)_2P(=O)Cl$-type chlorophosphate substrates, bis(aryl) chlorophosphates [32a] in acetonitrile and bis(2,6-dimethylphenyl) chlorophosphate [32b] in dimethyl sulfoxide to study the dual substituent effects on the reaction rate and mechanism. In both cases, the proposed mechanism is stepwise with rate-limiting leaving group expulsion from the intermediate involving a predominant backside nucleophilic attacktowards the leaving group based on following reasons: i) Positive sign of cross-interaction constant (ρ_{XY}) ii) Secondary inverse DKIES.

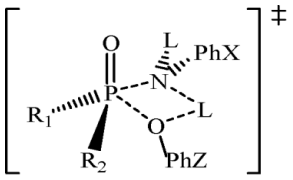
The severe steric hindrance of the two 2.6-dimethyl substituents prevents close proximity of aniline to the reaction center P atom. As a result, the considerably small value of $\beta_X(H) = 0.29$ and $\beta_X(D) = 0.31$ and greater magnitudes of k_H/k_D = 0.87-0.92 (i.e., smaller secondary inverse DKIEs) of bis(2,6-dimethylphenyl) chlorophosphate compared to bis(aryl) chlorophosphates (k_H/k_D = 0.55-0.98) are obtained.

On the other hand, Dey et al. (2011) [33a] performed the anilinolyses of $R_1R_2P(=O)OC_6H_4Z$ type phosphinates (Eq. 8) by varying R_1 and R_2.

$$R_1R_2P(=O)OC_6H_4Z + 2NL_2C_6H_4X \xrightarrow[60.0\ ^oC]{DMSO} R_1R_2P(=O)NLC_6H_4X + XC_6H_4\overset{+}{N}L_3O\overset{-}{C}_6H_4Z \quad (8)$$

1: $R_1 = R_2 =$ Me; **2:** R_1 = Me, R_2 = Ph; **3:** $R_1 = R_2$ = Ph
L = H (or D) when Z = 4-NO_2
X = 4-MeO, 4-Me, 3-Me, H, 3-MeO, 4-Cl, and 3-Cl
Z = 4-MeO, H, and 4-NO_2

As mentioned earlier, the steric effects (the two ligands: R_1 and R_2) upon the anilinolysis rates of this work do play a role over the inductive effects of the ligands, but rather a much smaller steric effect compared to earlier results: δ = 0.737 for the anilinolyses of three phosphinic chlorides [25a,c]; 0.478for the ethanolyses of three phosphinates; 0.345 for the hydrolyses of two phosphinates [30a,33b] (35, 23, and 16 times smaller, respectively). A step wise mechanism with a rate-limiting leaving group expulsion from the intermediate is proposed on the basis of the CICs positive signs. The dominant frontside nucleophilic attack through a hydrogen-bonded, four-center-type TS**IV** is proposed on the basis of primary normal DKIEs and large magnitudes of the CICs for **2** (ρ_{XZ} = 0.34, k_H/k_D = 1.15-1.29) and **3** ((ρ_{XZ} = 0.65, k_H/k_D=1.24-1.51), while both frontside and backside attack are proposed on the basisof relatively small primary normal DKIEs for **1**(k_H/k_D=1.03-1.17). Lee et al. (2013) [34] also studied the Anilinolysis of Aryl Ethyl Isothiocyanophosphates in Acetonitrile at 75°C. The free energy relationships with X in the nucleophiles exhibited biphasic concave downwards with a break point at X = H.



IV

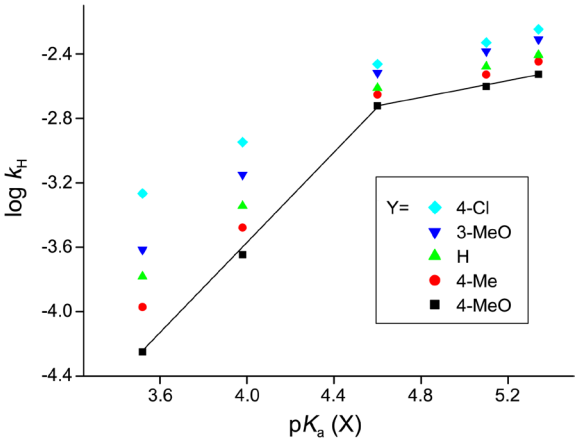
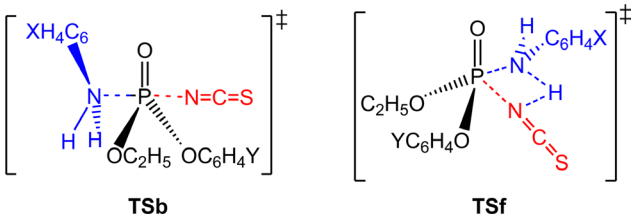


Figure 2. Brönsted plots with X [log kH vs pKa(X)] of the reactions of Y-aryl ethyl isothiocyanophosphates with XC6H4NH2 in MeCN at 75.0°C

A stepwise mechanism with rate-limiting bond formation for strongly basic anilines and with rate-limiting bond breaking for weakly basic anilines is proposed based on the negative and positive ρ_{XY} values, respectively. The deuterium kinetic isotope effects (DKIEs; k_H/k_D) changed gradually from primary normal with strongly basic anilines, via primary normal and secondary inverse with aniline, to secondary inverse with weakly basic anilines. The primary normal and secondary inverse DKIEs were rationalized by frontside attack involving hydrogen bonded, four-center-type TSf and backside attack involving in-line-type TSb, respectively.



Scheme 5. Backside attack involving in-line-type TSb and frontside attack involving a hydrogen bonded, four-center-type TSf

Barai et al.(2013) [35] reported the pyridinolysis of of bis(2-oxo-3-oxazolidinyl) phosphinic chloride and proposed a stepwise mechanism with arate-limiting step change from bond breaking for more basic pyridines to bond formation for less basicpyridines based on the selectivity parameters and activation parameters. Biphasic concave upward free energy relationship with X is ascribed to a change in the attacking direction of the nucleophile from a frontside attack with more basic pyridines to a backside attack with less basic pyridines.

3.3. Mechanism Changes at P=O

Nucleophilic substitution reactions at phosphorous center may proceed through change in mechanism at P=O centers. It is generally observed that changes from concerted to stepwise mechanism occur based on the properties of reactive amines.

Guha et. al [36] proposed a mechanism change from a concerted process for the weakly basic pyridines (X= 3-Cl – 4-CN) to a stepwise for the more basic pyridines (X =4-NH_2 – 3-CH_3) in the pyridinolysis of aryl bis (4-methoxyphenyl) Phosphatein acetonitrile at 55°C. A biphasic Bronsted plot obtained in this work, Fig.3. Generally the concerted path is favored by weakly basic nucleophiles and the stepwise path is favored by strongly basic nucleophiles [37]. The same trend observed in this work. The cross-interaction constant, ρ_{XZ} is negative (-1.98) for weakly basic nucleophiles for the concerted paths but ρ_{XZ} is positive (0.97) for the stepwise paths for strongly basic nucleophiles [5b]. The TS structures proposed as follows based on the cross-interaction constants.

The unusually large negative ρ_{XZ} value for the weakly basic nucleophiles indicates a TS, **V**, formed by the concerted front-side nucleophilic attack.

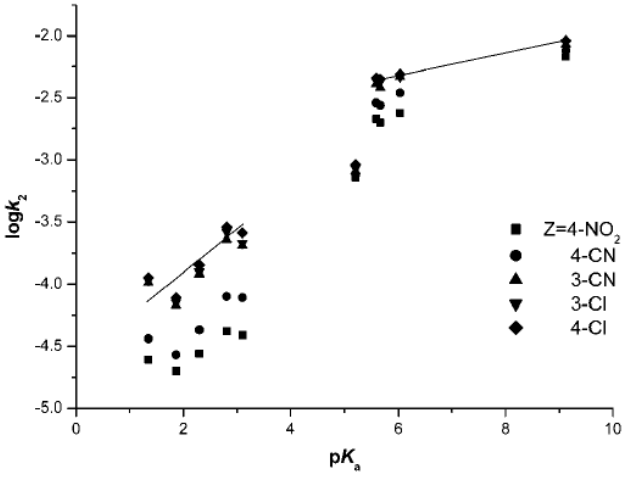
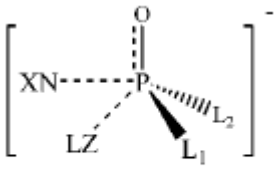


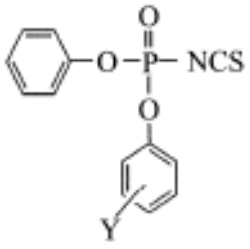
Figure 3. Plots of log k_2 vs pK_a(X- pyridines, in H_2O) for the reactions of Z-aryl bis(4-methoxyphenyl) phosphates with X-pyridines in acetonitrile at 55.0 °C



XN = NC_5H_4X
LZ = $^-OC_6H_4Z$
L_1, L_2 = 4-CH_3O-C_6H_4O

V

Adhikary et. al (2003) [38] reported exceptionally unusual mechanism change in the pyridinolysis of aryl phenyl isothiocyanophosphates, **VI,** in acetinitrile. Authors proposed mechanism change from a concerted to a stepwise with rate-limiting expulsion of the – NCS group from a TBP-5C intermediate. A convex upward biphasic type with a breakpoint at Y=H, hammett plots for substituent (Y) variations in the substrate obtained, Fig. 4. According to the Hammett plots for electron donating Y groups, ρ_Y are positive and cross-interaction constant ρ_{XY} is negative, while those for electron withdrawing Y groups, ρ_Y values are negative with a positive ρ_{XY}. Thes results are indicative of above mentioned mechanism change.



VI

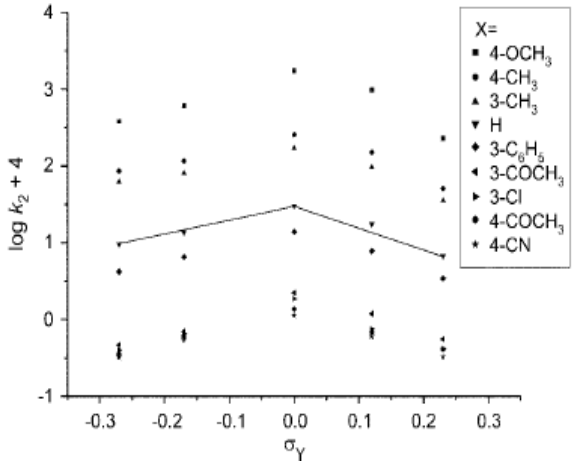


Figure 4. The Hammett plots for the Reactions of Y-aryl phenyl isothiocyanophosphates with X-pyridines in acetonitrile at 55°C

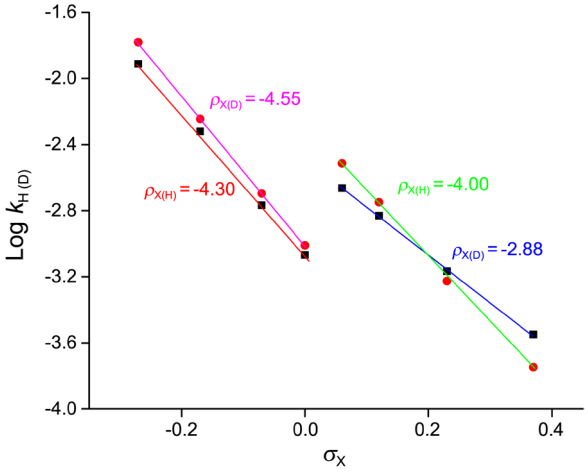


Figure 5. The Hammett plots (log kH(D) vs σX) of the reactions of diethyl isothiocyanophosphate (1) with XC6H4NH2(D2) in MeCN at 55.0 °C

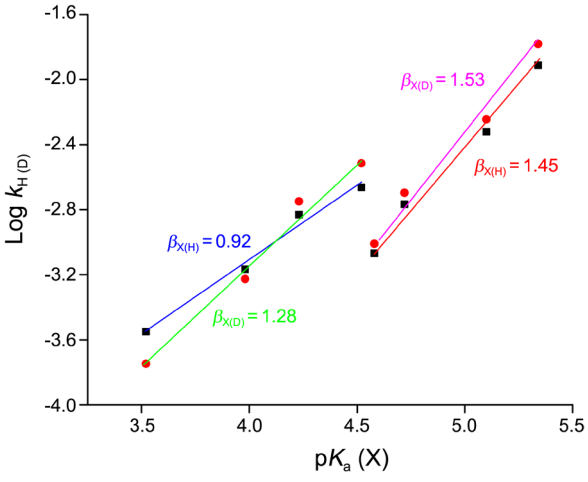


Figure 6. The Brönsted plots [log kH(D) vs pKa(X)] of of diethyl the reactions isothiocyanophosphate (1) with XC6H4NH2(D2) in MeCN at 55.0°C

Adhikary et. al (2012) [39] also reported mechanism change for anilinolysis of same leaving group containing substrate, diethyl isothiocyanophosphate in acetonitrile at

55°C. The Hammett and Brönsted plots for substituent X variations in the nucleophilesexhibit the two discrete slopes with a break region between X = H and 4-F Fig. 5and Fig. 6.The obtained DKIEs (k_H/k_D) are secondary inverse (k_H/k_D = 0.74-0.87) with the strongly basic anilines while secondary and primary normal (k_H/k_D = 0.71-1.58) with the weakly basic anilines. It is well known that chloride is a far better leaving group than isothiocyanate. The change of the leaving group from chloride to that of a poor leaving ability, isothiocyanate, can cause a change in mechanism from a concerted to a stepwise process with a rate-limiting breakdown of the trigonal bipyramidal pentacoordinate (TBP-5C) intermediate. This is in accord with the well established trend of the mechanistic change depending on the leaving groupability: the lower the leaving ability of the leaving group, the greater is the tendency for a stepwise mechanism with a rate limiting expulsion of the leaving group from the intermediate. The change in mechanism from a concerted to a stepwise reaction has been shown to occur by varying the strength of the nucleophile and leaving group in the neutral phosphoryl transfer reactions. The concerted path becomes more likely to be followed with less basic nucleophiles and with stronger leaving group. For very basic nucleophiles and poor leaving groups, a stepwise path is favoured [13]. Thus, the authors propose a concerted S_N2 mechanism (or a stepwise mechanism with a rate-limiting bond formation step) with the weakly basic anilines and a stepwise mechanism with arate-limiting leaving group departure from the TBP-5Cintermediate with the strongly basic anilines. The greatervalues of $\beta_X(H)$ = 1.45 and $\beta_X(D)$ = 1.53 with the stronglybasic anilines compared to those ($\beta_X(H)$ = 0.92 and $\beta_X(D)$ =1.28) with the weakly basic anilines are consistent with theproposed mechanism.

4. Conclusions

Phosphoryl transfer and related reactions are very much important in biological chemistry like basic metabolism and cellular signal transduction in living cells as well as in agricultural chemicals like pesticides and flame retardant chemicals used in textiles, plastic materials etc.

The mechanism of substitution reactions at phosphorous in solutions have been a subject of intensive study from which interesting results have emerged. Two main types of mechanism have been found in literature. Those are concerted and stepwise. In some cases mechanism change from concerted to stepwise found in these reaction series. These conclusions were drawn based on physical organic parameters and Cross-interaction constants. These review article includes exclusive review of reaction mechanism based on most recent results published in various Journals. As per published papers of pioneering groups of the World, we found concerted mechanism in pyridinolysis of phosphoryl pyridinium compounds, aminolysis of phenyl substituted phenyl chlorophosphate and other reactions. We also found stepwise mechanism in aminolysis of aryldiphenyl phosphinates. A mechanism change from a concerted process for the weakly basic pyridines (X= 3-Cl – 4-CN) to a stepwise for the more basic pyridines (X =4-NH_2 – 3-CH_3) in the pyridinolysis of aryl bis (4-methoxyphenyl) Phosphatein acetonitrile at 55°C was found in literature.

REFERENCES

[1] March, J. “Advanced Organic Chemistry”, 4th edition, Wiley interscience, New York, 1992.

[2] [a] Quin, L.D. “A guide to Organophosphorous Chemistry”, Wiley-Interscience, New York,2000, p 2.

[b] Hengge, A. C. 2005, “Mechanistic studies on enzyme-catalyzed phosphoryl transfer” Adv. Phys. Org. Chem., 40, 49-108.

[3] [a] Harger, M.J.P., “Nucleophilic substitution reactions of benzyl- and diphenylmethyl-phosphonamidic chlorides with amines: competition between the usual $S_N2(P)$ mechanism and elimination–addition with an alkylideneoxophosphorane (phosphene) intermediate”, J.Chem. Soc., perkin Trans. 2, 2001, 41.

[b] Hoque, M.E.U.; Dey, S.; Kim, C.K. and Lee, H.W. “Kinetics and Mechanism of the Pyridinolysis of Aryl Phenyl Chlorothiophosphates in Acetonitrile”, Bull. Korean Chem. Soc. 2011,32,1138.

[c] Domingos, J. B.; Longhinotti, E.; Buntor, C. A. and Nome, F.J. Org. Chem., 2003,68,305.

[d] Harger, M. J. P., “Methylenethioxophosphorane (thiophosphene) Intermediates in the Reactions of Diphenylmethyl phosponamidothioic Chlorides with amines. Differences between the Elimination – Addition Mechanisms of Nucleophilic Substitution for P=S and P=O Substrates”, J. Chem. Soc. Perkin Trans. 2: 2002, 489.

[e] Hengge, A. C., “Isotope effects in the Study of Phosphoryl and Sulfuryl Transfer Reactions”, Acc. Chem. Res., 2002, 35,105.

[f] Hengge, A. C., “Mechanistic Studies on Enzyne-Catalyze Phosphoryl Transfer” Adv. Phys. Org. Chem., 2005, 40, 49.

[g] Hengge, A. C. and Onyido, I. “Physical Organic Perspectives on Phospho Group Transfer from Phosphates to Phosphinates”, Curr. Org. Chem., 2005,9,61.

[h] Humphry, T.; Forconi, M.; Williams, N. H. and Hengge, A. C., “Altered Mechanisms of Reactions of Phosphate Esters Bridging a Dinuclear Metal Center”, J. Am. Chem. Soc.,2004,126,11864.

[i] Skoog, M. T. and Jencks, W. P. “Reactions of Pyridines and Primary amines with *N*- Phosphorylated pyridines”, J. Am. Chem. Soc., 1984,106,7597.

[j] Swamy, K. C. K. and Kumar, N. S., “New Features in Pentacordinated Phosphorus Chemistry”, Acc. Chem. Res., 2006, 39, 324.

[k] Thatcher, G. R. J. and Kluger, R., “Mechanism and Catalysis of Nuclephilic Substitution in Phosphate Esters.”1989, Adv. Phys. Org. Chem., 25, 199.

[l] Williams, A., "Concerted Organic and Bio-Organic Mechanisms", CRC: Boca Raton,2000, 54,130 pp.

[4] Williams, A., "Free Energy Relationship in Organic and Bio-Organic Chemistry", (UK: RSC Press), 2003.

[5] [a] Lee, I., "Characterization of Transition States for Reaction in Solution by Cross Interaction Constants."1990, Chem. Soc. Rev.,19, 317.

[b] Lee, I., 1992. "Cross-Interaction Constants and Transition State Structures", Adv. in Phys. Org. Chem., 27, 57.

[c] Lee, I., "Secondary Kinetic Isotope Effects Involving Deuterated Nucleophiles" Chem. Soc. Rev.1995, 24, 223.

[d] Lee, I. and Lee, H. W., "Cross-Interaction Constants, a Mechanistic Tool." Coll.Czech.Chem.Commun. 1999, 64, 1529.

[e] I. Lee, and Lee, H. W., "Cross Interaction Constant and Intrinsic Barrier", Bull. of Korean Chem. Soc. 2001, 22, 732.

[6] (a) Olaf, W.; Houk, K. N.; Black, K. A. and Thomas, B., J. Am.Chem. Soc., 1995, 117, 8594. (b) Carrol, F. A., "Perspectives on Structure and Mechanism in Organic Chemistry (ITP)", 1998. (c) Isaacs, N. S., "Physical Organic Chemistry(Longman: Harlow, 2nd ed)",1995.(d) Paneath, P. and O'Leary, M. H., J. Am.Chem.Soc.,1991,113,1691.

[7] [a] Adhikary, K. K.; Lumbiny, B. J.; Dey, S. and Lee, H. W.,, " Transition State Variation in the Anilinolysis of *O*-Aryl Phenyl Phosphonochloridothioates in Acetonitrile". Bull. of Korean Chem. Soc.,2011, 32, 2628.

[b] Lumbiny, B. J. and Lee, H. W., "Anilinolysis of *S*-Aryl Phenyl Phosphonochloridothioates in Acetonitrile," Bull. of Korean Chem.Soc.,2008, 29,2065.

[c] Hoque, M. E. U.; Dey, S.; Guha, A. K.; Kim, C. K.; Lee, B. S. and Lee, H. W., "Kinetics and Mechanism of the Aminolysis of the Aryl Phenyl Chlorophosphates with Anilines", J. Org. Chem.,2007, 72,5493.

[8] [a] Zalatan, J.; Herschlag, D.," Alkaline Phosphatase Mono- and Diesterase Reactions: Comparative Transition State Analysis", J. Am. Chem. Soc., 2006,128, 1293-1303.

[b] O'Brien, P. J.; Herschlag, D., "Functional interrelationships in the alkaline phosphatase superfamily: phosphodiesterase activity of Escherichia coli alkaline phosphatase," Biochemistry, 2001, 40, 5691-5699.

[c] Catrina, I. E., Hennge, A. C., "The effect of divalent metal ions on the rate and transition-state structure of phosphoryl-transfer reactions", J. Am. Chem. Soc., 1987,109, 4665-4674.

[9] Hansch, C.; Leo, A. and Taft, R. W. "Survey of Hammett Substituent Constants and Resonance and Field Parameters", Chem. Rev.,1991. 91,165-195.

[10] Zuman, P. and Patel, R. C., "Techniques In Organic Reactions Kinetics",(John Wiley and Sons, USA), 1984.

[11] Albert, A. and Serjeant, E. P., "The Determination of Ionization", (Chapman and Hall, New York, 3rd ed.),1984.

[12] [a] Lee, I.; Kang, H. K. and Lee, H. W., J. Am. Chem. Soc.,1987, 109, 7472.

[b] Lee, I.; and Lee, H.W., "Cross-interaction constants as ameasure of the transition-state structure. 14. Nucleophilic substitution reactions of 1-phenyl-2-propylbenzenesulfonates with anilines in methanol", J. Org. Chem., 1991, 56, 4682.

[c] I. Lee, "Bimolecular nucleophilic substitution at a resonance-stabilized carbenium ion: Elevated value of cross-interaction constant, imbalanced transition state and the non-interactive phenomenon", J. Phy. Org. Chem., 1994,7, 448.

[d] Guha, A.K.; Lee, H.W. and Lee, I., 1999, "Kinetics and mechanism of the aminolysis of phenyl substituted phenyl chlorophosphates with anilines in acetonitrile", I. J. Chem. Soc., Perkin Trans. 2, 1999, 765.

[13] Bourne, N. and Williams, A. "Evidence for a single transition state in the transfer of the phosphoryl group (-PO32-) to nitrogen nucleophiles from pyridinio-N-phosphonates" J. Am. Chem. Soc., 1984, 106, 7591.

[14] Bourne, N.; Chrystiuk, F.; Davis, A. M. and Williams, A. "A single transition state in the reaction of aryl diphenylphosphinate esters with phenolate ions in aqueous solution", J. Am. Chem. Soc., 1988, 110,1890.

[15] Guha, A.K.; Lee, H.W. and Lee, I., "Pyridinolysis of Phenyl-Substituted Phenyl Chlorophosphate in Acetonitrile", 2000, J. Org. Chem., 65, 12-15.

[16] Dewar, M. J. S. "The Molecular orbital Theory of Organic Chemistry", McGraw-Hill:New York, 1969,p 358.

[17] Lee, H. W. and Guha, A. K., Lee, I., "Kinetics and mechanism of the reaction of *para*-chlorophenyl aryl chlorophosphates with anilines in acetonitrile", Int. J. Chem. Kinet, 2002, 34,632.

[18] Lee, I.;, Kim, C. K.; Li, H. G.; Sohn, C. K.;C. K. Kim, H. W. Lee and B. S. Lee, "Acyl-Transfer Mechanisms Involving Various Acyl Functional Groups: >X═Y with X = C, S, P and Y = O, S", J. Am.Chem.Soc., 2000, 122, 11162.

[19] Um, I.H.; Shin, Y. H; Han, J. Y. and Mishima, M. "Aminolysis of Y- Substituted Phenyl Diphenyl Phosphinates and Benzoates: Effect of Modification of Electrophilic center from C=O to P=O" J. Org. Chem, 2006, 71, 7715-7720.

[20] Hoque, M.E.U.; Dey, N. K.;Kim, C. K., Lee, B. S. and Lee, H. W. "Kinetics and mechanism of the aminolysis of aryl ethyl chloro and chlorothio phosphates with anilines", Org. Biomol. Chem., 2007,5, 3944-3950.

[21] Um, G. H.; Han, J. Y. and Shin, Y. H. "Aminolysis of X-Substituted Phenyl Diphenylphosphinates: Effect of Amine Nature on Reactivity and Transition-State Structure", J. Org. Chem, 2009, 74, 3073-3078.

[22] [a] Dey, N.K.; Hoque, M. E. U. ; Kim, C. K.; Lee, B. S. and Lee, H. W. " Kinetics and mechanism of the anilinolysis of dimethyl and diethyl chloro(thino) phosphates", J.Phy.Org.Chem., 2008,21, 544-548.

[b] Hoque, M. E. U. and Lee, H. W., "Kinetics and Mechanism of the Anilinolysis of Dipropyl Chlorophosphate in Acetonitrile, Bull. Korean. Chem. Soc., 2012,33 (6) 1879.

[c] Hoque, M. E. U. andLee, H. W., "Kinetics and Mechanism of the Anilinolysis of Dibutyl Chlorophosphate in Acetonitrile, Bull. Korean. Chem. Soc., 2012,33(2) 663.

[d] Hoque, M. E. U. and Lee, H. W., "Kinetics and Mechanism of the Anilinolysis of Diisopropyl Chlorophosphate in Acetonitrile, Bull. Korean. Chem. Soc.,

2011, 32(9), 3245.

[23] Taft, R. W. "Steric Effects in Organic Chemistry", Newman, M.S., Wiely, New York, Chapter 3.1956.

[24] Hoque, M. E. U. and Lee, H. W., "Pyridinolysis of Dibutyl Chlorophosphate in Acetonitrile", 2012,33(3), 1055.

[25] [a] Dey, N.K.; Hoque, M. E. U.; Kim, C. K.; Lee, B. S. and Lee, H. W., " Kinetics and mechanism of the aminolysis of dimethyl and methyl phenyl phosphinic chlorides with anilines", J.Phy.Org. Chem., 2009, 22, 425-430.

[b] Dey, N. K. and Lee, H. W., "Anilinolysis of diethyl pphosphinic chloride in Acetonitrile", Bull. Korean. Chem. Soc., 2010,31(5), 1403.

[c] Hoque, M. E. U. and Lee, H. W. "Kinetics and Mechanism of the Aminolysis of Diphenyl Phosphinic Chloride with Anilines", Bull. Korean Chem. Soc.,2007,Vol. 28, No. 6, 936-940.

[d] Hoque, M. E. U. and Lee, H. W., "Kinetics and Mechanism of the Anilinolysis of Dicyclohexyl phosphinic Chloride in Acetonitrile", Bull. Korean Chem. Soc.,2011, Vol. 32, 6, 1997.

[26] Hong, H.J.; Lee, J.; Bae, A. R. and Um, I. H., "Kinetics and Reaction Mechanism for Alkaline Hydrolysis of Y-Substituted-Phenyl Diphenylphosphinates", Bull. Korean Chem. Soc., 2013, Vol. 32, 6 , 2001-2005.

[27] Barai, H. R. and Lee, H. W., "Kinetics and Mechanism of the Aminolyses of Bis(2-oxo 3-oxazolidinyl) Phosphinic Chloride in Acetonitrile", Bull. Korean Chem. Soc.,2013, Vol. 34, 11.

[28] Cook, R. D.; Daouk, W. A.; Hajj, A. N.; Kabbani, A.; Kurku, A.; Samaha, M.; Shayban, F. and Tanielian, O. V.,Can. J. Chem., 1986, 64, 213- 219.

[29] [a] Cook, R. D.; Rahhal-Arabi, L., "The kinetics of the alkaline hydrolysis of aryl diphenylphosphinothioates; the significance for the mechanism of displacement at phosphorus", Tetrahedron Lett.,1985,26, 3147-3150.

[b] Haake, P.; McCoy, D. R.; Okamura, W.; Alpha, S. R.; Wong, S. W.; Tyssee, D. A.; McNeal, J. P. and Cook, R. D., "Phosphinic acids and derivatives. 4. Linear free energy relationships in displacement at phosphinyl phosphorus" *Tetrahedron Lett*. 1968, 5243-5246.

[30] [a] Williams, A. and Naylor, J., , "Hydrolysis of phosphinic esters: general-base catalysis by imidazole" J. Chem. Soc.1971, 1967-1972.

[b] Buncel, E.; Albright, K. G. and Onyido, I., "Nucleophilic displacement on 4-nitrophenyl dimethyl phosphinate by ethoxide ion: alkali metal ion catalysis and mechanism", 2004,2, 601-610.

[31] Domingos, J. B.; Longhinotti, E.; Bunton C. A. and Nome, F, "Reactions of bis(2,4-dinitrophenyl) phosphate with hydroxylamine", J. Org. Chem., 2003, 68, 7051-7058.

[32] [a] Barai, H. R. and Lee, H. W., "Kinetics and Mechanism of the Anilinolysis of Bis(aryl) Chlorophosphates in Acetonitrile", Bull. Korean Chem. Soc., 2011, 32(6), 1939.

[b] Barai, H. R.; Lee, H. W., "Kinetics and Mechanism of the Anilinolysis of Bis(2,6-dimethylphenyl) Chlorophosphate in Dimethyl Sulfoxide", Bull. Korean Chem. Soc., 2011, 32(10), 3783.

[33] [a] Dey, N. K.; Kim, C. K. and H. W. Lee, "Kinetics and mechanism of the anilinolyses of aryl dimethyl, methyl phenyl and diphenyl phosphinates", Org. Biomol. Chem., 2011,9, 717.

[b] Douglas, K. T. and Williams, A., "Nucleophilic *versus* general base catalysis in phosphyl (P^V) group transfer: application to α-chymotrypsin action", J. Chem. Soc, Perkin Trans 2., 1976,515.

[34] Barai, H. R.; Adhikary, K. K. and Lee, H.W., "Kinetics and Mechanism of the Anilinolysis of Aryl Ethyl Isothiocyanophosphates in Acetonitrile", Bull. Korean Chem. Soc., 2013, 34(6), 1829.

[35] See Reference 27.

[36] Lee, H. W.; Guha, A. K.; Kon C. K.and Lee, I., "Transition-State Variation in the Nucleophilic Substitution Reactions of Aryl Bis(4-methoxyphenyl) Phosphates with Pyridines in Acetonitrile", J. Org. Chem., 2002,67, 2215.

[37] [a] Rowel, R.; Gorenstein, D. G., "Multiple structure-reactivity correlations in the hydrolysis of epimeric 2-aryloxy-2-oxy-dioxaphosphorinanes. Stereoelectronic effects", J. Am., Chem. Soc., 1981, 103, 5894.

[b] Ba-saif, S. A.; Waring, M. A. and Williams, A. "Single transition state in the transfer of a neutral phos;phoryl group between phenoxide ion nucleophiles in aqueous solution", J. Am. Chem. Soc., 1990,112, 8115.

[38] Adhikary, K. K.; Lee, H. W. and Lee, I., "Kinetics and Mechanism of the Pyridinolysis of Aryl Phenyl Isothiocyanophosphate in Acetonitrile", Bull. Korean. Chem. Soc.,2003,24, 1135.

[39] Barai, H. R.; Adhikary, K. K. and Lee, H. W., "Anilinolysis of diethyl isothiocyanophosphate in acetonitrile." Bull. Korean. Chem. Soc.,2012, 33, 3, 1089.