

Kinetic Approach to Hydrolysis of Mono-6-Chloro-2, 4-Dinitroaniline Phosphate in Acidic Medium

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Abstract- Phosphate ester hydrolysis plays a very important role in many biological processes. The present investigation belongs to study of kinetic behavior of acid catalyzed hydrolysis of mono-6-chloro-2, 4-dinitroaniline phosphate in 0.1-7.0 mol dm⁻³ HCl at 50°C in aqueous medium. The log rate profile shows that the rate of reaction increases up to 4.0 mol dm⁻³ HCl. The results show that mono-6-chloro-2, 4-dinitroaniline phosphate is reactive mainly via conjugated acid species. Positive salt effect has been exhibited through ionic strength data. Behavior of molecularity and order of reaction have been estimated by the use of different concepts and hypothesis, such as Hammett acidity function, Zucker-Hammett hypothesis, Bunnett, Bunnett-Olsen and Arrhenius parameters. Isokinetic relationship has been applied to propose probable reaction mechanism for the hydrolysis. Experimental rate coefficients have been found to agree well with theoretical rates in the entire acid range.

Index Terms- Hydrolysis, mono-6-chloro-2,4-dinitroaniline phosphate, molecularity, bond-fission.

I. INTRODUCTION

Phosphate esters are the derivatives of phosphoric acid which may be esterified in one, two, or three positions, forming monoester, diester or triester respectively¹. The role of phosphate esters having different linkages as C-O-P, C-N-P, C-S-P are well known in various branches of chemistry. Phosphate esters control a significant part of living system from genetic material, coenzyme to energy storing compounds and signaling agents^{2, 3}. Tri-esters do not occur naturally, but together with related compounds have found widespread use as herbicides and insecticides⁴. Phosphate esters are normally considered as important pharmacological compounds and have received an increasing amount of attention due to their significant biological interests⁵. They are used as fungicides, antiviral, antitumor agents⁶⁻⁷. In addition to their biological significance, they are proved to be of great technical importance for industries. They are used as additives in petroleum, flame retardants, corrosion inhibitors, and smoke generation⁸⁻¹⁰. The facile hydrolysis of these organophosphate esters is found everywhere and has attracted a great consideration due to their great values in various chemical and biochemical reactions¹¹⁻¹³. Thus it has become the subject of intense research to the chemists and biologists.

II. EXPERIMENTAL

Mono-6-chloro -2, 4- dinitroaniline phosphate ester has been synthesized by Cavalier method¹⁴, which involves the reaction of

6-chloro-2,4-dinitroaniline with phosphorylating agent phosphorus pentoxide (P₂O₅) in 1:1 mol ratio by weight in benzene. Hydrolytic reactions of mono-6-chloro-2, 4-dinitroaniline phosphate ester has been carried out at 50 ± 0.5°C and concentration of ester was kept constant at 5.0 x 10⁻⁴ mol dm⁻³. The progress of kinetics of hydrolysis has been studied by Allen's modified method¹⁵. The constant ionic strengths have been maintained by using the mixture of HCl and NaCl. First-order rate coefficients have been determined from the first-order rate equation. All the chemicals used were of A. R. quality. HCl was standardized by N/10 sodium tetra borate (Borax) solution. Triple distilled water has been used in all experiments.

III. RESULT AND DISCUSSION

Hydrolysis via conjugate acid species

In order to understand the behavior of mono-6-chloro-2, 4-dinitroaniline phosphate during the hydrolysis i.e. involvement of its reactive forms as well as their modes of hydrolysis, kinetic runs were performed in 0.1 to 7.0 mol dm⁻³ HCl at 50°C. The first order rate coefficients obtained are shown in Table II and illustrated in figure 1. From the result it is observed that in acid region rate of hydrolytic reaction increases with increase in acid molarity up to 4.0 mol dm⁻³ HCl and after that decreases. The initial rise in rate in acid media may either be due to complete conversion of substrate in to its conjugate acid species (acid catalyzed reaction). Decrease in rate was attributed to lowering of the concentration of attacking nucleophile in the reaction i.e. due to variation in water activity.

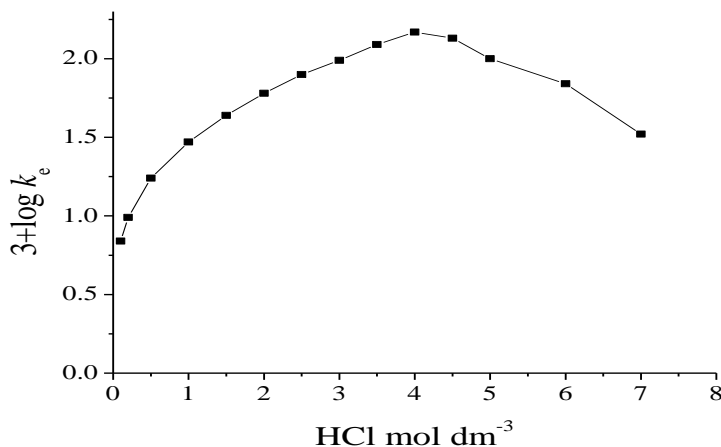


Figure 1: The plot of $3+\log k_e$ versus HCl mol dm^{-3} for acid catalyzed hydrolysis of mono-6-chloro-2, 4-dinitroaniline phosphate

Kinetic Salt Effect

In order to understand the salt effect kinetic runs were performed at different constant ionic strength using appropriate molarities of hydrochloric acid (HCl) and sodium chloride

(NaCl). Plot of rate coefficients of acid hydrolysis and acid molarities is illustrated in Figure 2.

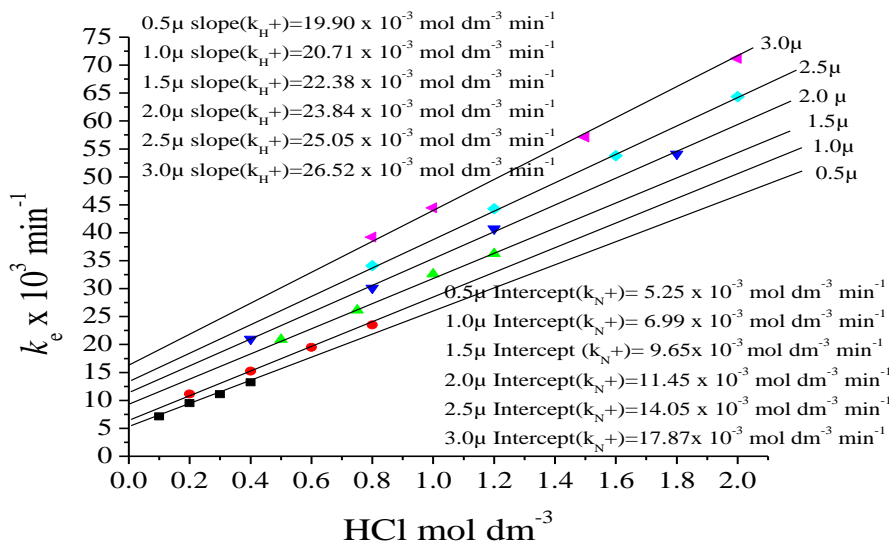


Figure 2: Acid catalyzed hydrolysis of mono-6-chloro-2, 4-dinitroaniline phosphate at constant ionic strength

Hydrolysis at each ionic strengths (μ) is denoted by six straight lines that make a positive slope with acid axis, hydrolysis is subjected to acid-catalysis. The slope of straight lines increases with increase in ionic strength. Thus acid catalyzed hydrolysis is attributed to positive salt effect. Straight lines meet at different points on rate axis indicate that there is involvement of other species in addition to conjugate acid species. The possibility of

neutral species can not be ignored due to the fact that mononegative species can not be reactive at higher concentration more than 1.0 mol dm^{-3} . Linear curves are intercepting the rate axis at different points which show that the contribution of neutral species at different acidities is varying. Specific acid catalyzed rate with their logarithmic values at that ionic strength are summarized in Table I and illustrated in Figure 3.

Table I: Specific Acid Catalyzed rates for the hydrolysis of mono-6-chloro-2, 4-dinitroaniline phosphate via its conjugate acid and neutral species

Ionic Strength μ	$k_H^+ \times 10^3$ (min^{-1})	$3+\log k_H^+$	$k_N^+ \times 10^3$ (min^{-1})	$3+\log k_N^+$
0.5	19.90	1.30	05.25	0.72
1.0	20.71	1.32	06.99	0.84
1.5	22.38	1.35	09.65	0.98
2.0	23.84	1.38	11.47	1.06
2.5	25.05	1.40	14.05	1.15
3.0	26.52	1.42	17.87	1.25

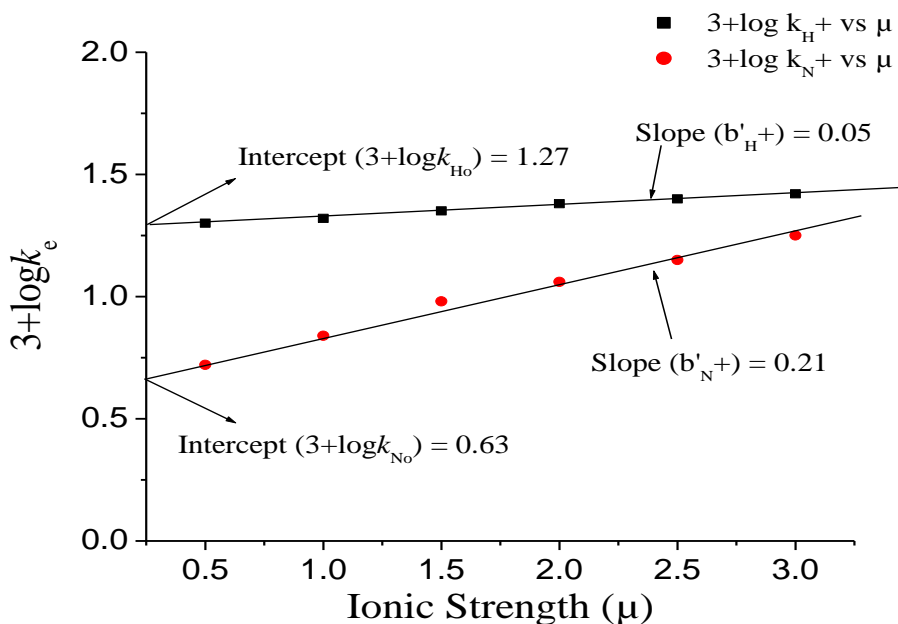


Figure 3: Plot of $3+\log k_e$ versus ionic strength (μ) for acid catalyzed hydrolysis of mono-6-chloro-2, 4-dinitroaniline phosphate

The slope of lines represents a constant, b'_{H^+} which is equal to $b'_{H^+} / 2.303$ and intercepts on rate axis represent the specific acid catalyzed rate (k_H^+). From the study of ionic strength effect, the total rates contributed by conjugate acid and neutral species can be calculated by the following 2nd empirical term of Debye-Huckel equation¹⁶.

$$k_e = k_H^+ \cdot C_{H^+} + k_N \quad (1)$$

where k_e , $k_H^+ \cdot C_{H^+}$, k_N are observed rate coefficient, specific acid catalyzed rate and specific neutral rate at that ionic strength respectively.

Specific acid catalyzed rate and neutral rate can be presented by following equation:

$$k_H^+ \cdot C_{H^+} = k_{H_3O^+} \cdot C_{H_3O^+} \cdot \exp. b'_{H^+} \cdot \mu \quad (2)$$

$$k_N = k_{N_0} \exp. b'_{N^+} \cdot \mu \quad (3)$$

Equation 1 was used to determine the calculated rates. Table II summarizes both the estimated and experimental rate of the hydrolysis in acid region from 0.1 to 7.0 mol dm⁻³ HCl. The lowering in rate after 4.0 mol dm⁻³ may be due to the lowering in the concentration of water molecules. The rate beyond 4.0 mol dm⁻³ HCl was calculated employing the Bronsted Bjerrum Equation¹⁷.

$$k_e = k_H^+ C_{H^+} (a_{H_2O})^n + k_N (a_{H_2O})^n \quad (4)$$

Table II : Estimated and experimental rate data for acid catalyzed hydrolysis of mono-6-chloro-2, 4-dinitroaniline phosphate ester

HCl (mol dm ⁻³)	$k_{H^+} \cdot C_{H^+}^x \cdot 10^3$ (min ⁻¹)	$k_N \times 10^3$ (min ⁻¹)	$-\log$ (a_{H_2O}) ⁿ	$k_e \times 10^3$ (min ⁻¹) Estd.	$k_e \times 10^3$ (min ⁻¹) Expt.	3+log k_e Estd.	3+log k_e Expt.
0.1	1.86	4.47	-	06.33	06.94	0.80	0.84
0.2	3.80	4.68	-	08.48	09.88	0.93	0.99
0.5	10.00	5.50	-	15.50	17.33	1.19	1.24
1.0	20.89	6.92	-	27.81	29.60	1.44	1.47
1.5	33.88	8.91	-	42.79	43.31	1.63	1.64
2.0	46.77	11.22	-	57.99	60.81	1.76	1.78
					67.11 ^a		
					74.19 ^b		
					83.18 ^c		
					90.07 ^d		
2.5	63.10	14.45	-	77.55	78.90	1.89	1.90
3.0	79.43	18.20	-	97.63	98.92	1.99	1.99
3.5	97.72	23.44	-	121.16	122.54	2.08	2.09
4.0	117.49	29.51	-	147.00	148.89	2.17	2.17
4.5	104.71	28.18	(0.13) ¹	132.89	133.51	2.12	2.13
5.0	79.43	22.91	(0.16) ²	102.34	99.83	2.01	2.00
6.0	52.48	18.20	(0.21) ³	70.68	69.23	1.85	1.84
7.0	22.39	9.55	(0.28) ⁴	31.94	32.97	1.50	1.52

Note: a=10% Dioxane, b=20% Dioxane, c=30% Dioxane, d=40% Dioxane

Where n is an integer and a_{H_2O} is water activity. The estimated rates agree well with the experimentally observed rates. It is clear from the results that hydrolysis of mono-6-chloro-2, 4-dinitroaniline phosphate in acid occurs via both conjugated acid species and neutral species, and their rates are subjected to positive ionic strength or water activity.

Molecularity of the Hydrolytic Reaction-

Zucker-Hammett Hypothesis¹⁸ is made up of two parts, in the first part Hammett Postulated¹⁹, that the reactions which give linear plot of log rate constants against acidity function ($-H_o$) did not involve water molecule in rate determining step (i.e.

unimolecular hydrolysis). The slope value 0.59 (± 0.02) of the plot (figure not shown) is far from unity, indicating the absence of unimolecular hydrolytic reaction of phosphate ester.

Second part of hypothesis deals with a plot between the log rate constant and log acid molarities. A unit or approximately unit slope of plot was used as a criterion to predict the probable mechanism to be bimolecular, i.e. reaction involves the participation of water molecule in the transition state (Scheme 1). The slope value 1.17 (± 0.05) clearly shows the bimolecular nature of the reaction, data is presented in Table III (figure not shown).

Table III : Hammett and Zucker Hammett plot rate data for the hydrolysis of mono-6-chloro-2, 4-dinitroaniline phosphate

HCl (mol dm ⁻³)	$k_e \times 10^3$ (min ⁻¹)	3+log k_e	$-H_o$	log C_{H^+}
1.0	29.60	1.47	0.20	0.00
1.5	43.31	1.64	0.47	0.18
2.0	60.81	1.78	0.69	0.30
2.5	78.90	1.90	0.87	0.40
3.0	98.92	1.99	1.05	0.48
3.5	122.54	2.09	1.23	0.54
4.0	148.89	2.17	1.40	0.60
4.5	133.51	2.13	1.58	0.65
5.0	99.83	2.00	1.76	0.70
6.0	69.23	1.84	2.12	0.78
7.0	32.97	1.52	2.53	0.85

Table IV : Bunnett and Bunnett-Olsen plot rate data for the hydrolysis of mono-6-chloro-2, 4-dinitroaniline phosphate

HCl (mol dm ⁻³)	$k_e \times 10^3$ (min ⁻¹)	3+log k_e	3+log $k_e + H_o$	3+log $k_e - \log C_{H^+}$	-log a_{H_2O}	- log $C_{H^+} + H_o$
1.0	29.60	1.47	1.27	1.47	0.02	0.20
1.5	43.31	1.64	1.17	1.46	0.03	0.29
2.0	60.81	1.78	1.09	1.48	0.04	0.39
2.5	78.90	1.90	1.03	1.50	0.05	0.47
3.0	98.92	1.99	0.94	1.51	0.07	0.57
3.5	122.54	2.09	0.86	1.55	0.09	0.69
4.0	148.89	2.17	0.77	1.57	0.11	0.80
4.5	133.51	2.13	0.55	1.48	0.13	0.93
5.0	99.83	2.00	0.24	1.30	0.16	1.06
6.0	69.23	1.84	-0.28	1.06	0.21	1.34
7.0	32.97	1.52	-1.01	0.67	0.28	1.68

Some other correlation plots like Bunnett plot²⁰ in which log $k_e + H_o$ is plotted against log a_{H_2O} and another plot is plotted between log $k_e \cdot \log C_{H^+}$ and log a_{H_2O} . The slope values are $\omega = 7.20 (\pm 0.39)$, $\omega^* = 3.22 (\pm 0.31)$ respectively. Bunnett and Olsen²¹ plot is plotted between $k_e + H_o$ vs $-(\log C_{H^+} + H_o)$ and obtained slope value is $\phi = 1.18 (\pm 0.05)$. These slope values suggested a bimolecular nature of hydrolysis in which water is involved as a proton transfer agent in the rate determining step. Data are shown in Table IV (figures not shown).

Chemical reactions can be affected by the solvent through several kinds of interactions. Table II shows significant rise in rates with increase in percent of dioxane in water. Dioxane is regarded as a polar aprotic solvent and being a better proton

donor than water. It increases the concentration of conjugated species resulting in the increase in rate. Effect of solvent on rate of the hydrolysis indicates the transition state in which charge is dispersed out. This is in accordance with Chanley's observation²². Further evidences regarding molecularity and rigidity of transition state with probable mechanism of hydrolysis can be obtained by Arrhenius parameters²³. Arrhenius parameters were determined for the hydrolysis of mono-6-chloro-2,4-dinitroaniline phosphate at 2 and 6 mol dm⁻³ HCl and presented in Table V. The results favor the bimolecular nature of hydrolytic reaction.

Table V: Arrhenius plot data for the hydrolysis of mono-6-chloro-2, 4-dinitroaniline phosphate

HCl (mol dm ⁻³)	Parameters			
	Slope	E_a (Kcal/mol)	A (sec ⁻¹)	$-\Delta S^\ddagger$ (e.u.)
2	-0.025	11.44	1.99×10^8	30.89
6	-0.024	10.98	1.12×10^8	32.01

A comparative kinetic rate data for hydrolysis of some phosphate monoesters also support the bimolecular nature of hydrolysis of mono-6-chloro-2, 4-dinitroaniline phosphate involving with the cleavage of P-N bond by attack of water

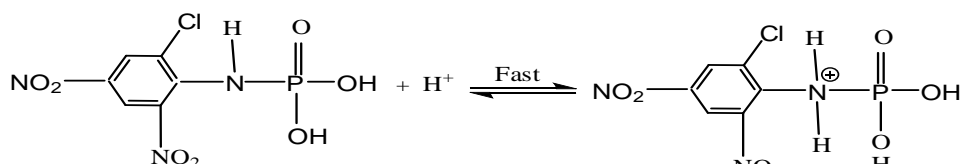
molecule on phosphorus of the monoester are mentioned in Table VI.

Table VI : Comparative kinetic rate data for the the hydrolysis of some phosphate monoester via their conjugate acid species

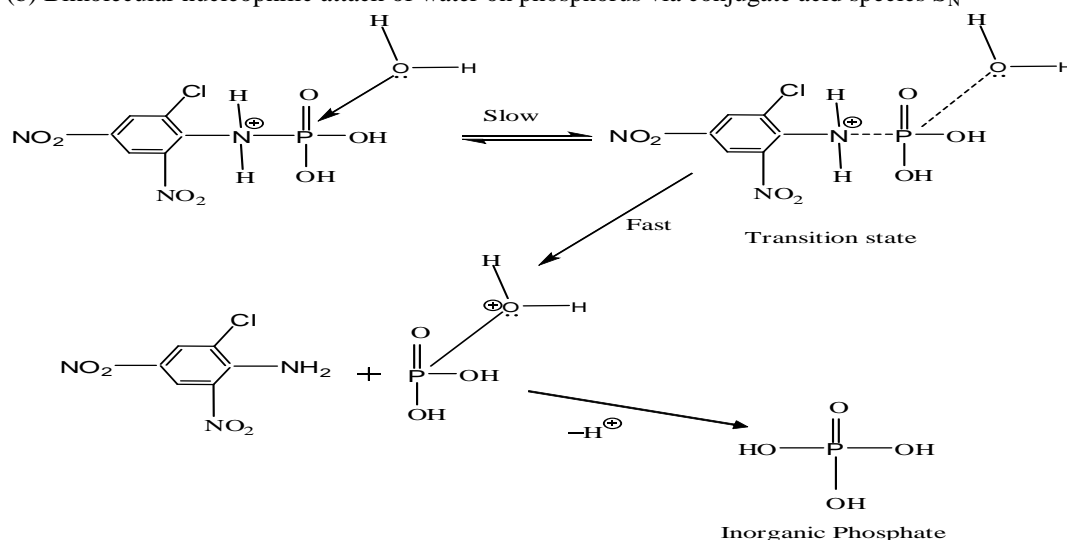
Phosphate monoesters	HCl (mol dm ⁻³)	E_a (Kcal/mol)	$-\Delta S^\ddagger$ (e.u.)	Molecularity	Bond fission
Mono-p-toluidine	4	11.89	28.48	2	P-N
2-nitro-4-methoxyaniline	4	6.61	54.80	2	P-N
p-nitro aniline	3	15.25	9.50	2	P-N
2,4-dinitrophenyl hydrazo	3	6.44	55.47	2	P-N
2,4-dinitrophenyl hydrazo	5	5.94	56.86	2	P-N
2-methyl-5-nitroaniline	3	14.64	20.79	2	P-N
2-methyl-5-nitroaniline	4	13.73	22.87	2	P-N
6-chloro-2,4-dinitroaniline*	2*	11.44*	30.88*	2*	Present
	6*	10.98*	32.03*	2*	work*

Mechanism of Hydrolysis

(a) Formation of conjugate acid species by a fast pre equilibrium proton transfer:



(b) Bimolecular nucleophilic attack of water on phosphorus via conjugate acid species S_N^2



IV. CONCLUSIONS

Acid catalyzed hydrolysis of mono-6-chloro-2, 4-dinitroaniline phosphate in $0.1 - 7.0 \text{ mol dm}^{-3}$ was found to proceed via neutral and conjugate acid species. The acid catalyzed hydrolysis is subjected to the positive salt effect of ionic strength. Bimolecular nature of hydrolysis was supported by different concepts and hypothesis such as Hammett, Zucker Hammatt, and Bunnett, Bunnett Olsen. Arrhenius parameters also supported the bimolecular nature of reaction. Bimolecular attack of water on phosphorus of the mono-6-chloro-2, 4-dinitroaniline phosphate is taken to proceed via P-N bond fission. Isokinetic relationship plots among the same type of esters whose mechanism is already known supported the P-N fission of bond. S_N^2 (P) mechanism was suggested for the hydrolysis via conjugate acid species.

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