# A CATALYTIC EFFECT OF THE CHLORIDE ION ON THE KINETICS OF CHLORINATION OF AROMATIC SUBSTRATES BY CHLORINE IN AQUEOUS SOLUTION

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## ABSTRACT

The chloride ion has been found to remarkably enhance the specific rates of chlorination of aromatic substrates containing electron-releasing groups by chlorine in aqueous solution. The specific rate varies linearly with concentration of the added chloride ion. This is associated with a fall in the activation energy. The enhancement of specific rate by the chloride ion due to suppression of hydrolysis of chlorine, the formation of trichloride ion, base catalysis or salt effect have been shown to be improbable. The mechanism suggested to explain the catalytic effect of the chloride ion postulates a longer mean life for the $Cl\overset{\delta+}{-}\overset{\delta-}{Cl}$ dipole induced by the aromatic substrate by electron rearrangement with the chloride ion, which facilitates the formation of the positively charged intermediate.

## INTRODUCTION

THE accepted mechanism for the chlorination of aromatic substrates containing electron-releasing groups by molecular chlorine involves polarization of the Cl-Cl bond followed by electrophilic attack by the positive end of the dipole[1]. The mechanism hardly suggests any possibility of the chloride ion influencing the reaction rate. We have, however, observed that the chloride ion remarkably enhances the rate of such chlorinations. A similar feature, but in a much smaller measure, was reported by Keefer and Andrews[2] and Stock *et al*[3] in chlorinations by hypochlorous acid in acetic acid. In contrast, in the chlorination of aromatic substrates by molecular chlorine in aqueous solution, such an effect has not been reported. In order to assess the role of chloride ion in such reactions, the present study has been undertaken with several typical aromatic substrates, such as salicyclic acid, 2,4-dihydroxy benzoic acid, acetanilide and 2-methyl acetanilide.

These reactions are too rapid to be studied by conventional techniques and hence these have been studied by the voltammetric principle using a rotating platinum electrode, (RPE)[4]. Chlorine gives diffusion current proportional to its concentration at the RPE, whereas neither the aromatic substrate nor the products yield any diffusion current. Hence the course of reaction can be followed by measuring the diffusion current at intervals of time. This technique yields quite reproducible results in the kinetic study of the rapid bromination of aromatic substrates by bromine[5] and by acidified hypohalous acid[6]. The voltammetric principle, but with the platinum electrode in flowing solution, was successfully used in studying the rapid bromination of salicylic acid[7].

## EXPERIMENTAL

Analytical grade chemicals were used to prepare solutions of $2.0 \times 10^{-4}$ M chlorine (A) and $2.0 \times 10^{-4}$ M salicylic acid (B), each containing $1.0 \times 10^{-2}$ M potassium nitrate as supporting electrolyte. The solutions were maintained at 25°C in a thermostat.

The diffusion current of chlorine was first calibrated. The RPE and a saturated calomel electrode were introduced into several chlorine solutions of concentration $0.2 \times 10^{-4} - 1.0 \times 10^{-4}$ M, each in $1.0 \times 10^{-2}$ M potassium nitrate. The diffusion current in each case was measured and plotted with the concentration of chlorine.

For kinetic measurements, 50 $cm^3$ aliquots of solutions (A) and (B) were simultaneously poured into a beaker containing the electrode assembly. The resulting reactant concentration was each $1 \times 10^{-4}$ M and the ionic strength was 0.01 M. The reaction was followed by noting the diffusion current at intervals of time. Since the reaction was of second order, the reciprocal of concentration of the unreacted chlorine (obtained from calibration curve) versus time was plotted. A straight line was obtained whose slope was the specific rate, $k_2^0$.

Several repeated determinations of the specific rate yielded results reproducible to within $\pm 2\%$.

The kinetic measurements were repeated in the presence of added potassium chloride from a ten-fold

**Table 1** *Effect of chloride ion on the kinetics of chlorination of aromatic substrates by chlorine in aqueous solution at 25.0°C*

| | Salicylic acid | 2,4-Dihydroxy benzoic acid | Acetanilide | 2-Methyl acetanilide |
|---|---|---|---|---|
| Specific rate in the absence of added chloride ion $k_2^0/M^{-1}sec^{-1}$ | 2.00 | 14.3 | 0.38 | 0.49 |
| Specific rate in the presence of hundred-fold relative concentration of chloride ion $k_2^{Cl^-}/M^{-1}sec^{-1}$ | 179 | 484 | 35.6 | 13.0 |
| $k_2^{Cl^-}/k_2^0$ | 89.5 | 33.9 | 93.7 | 26.5 |

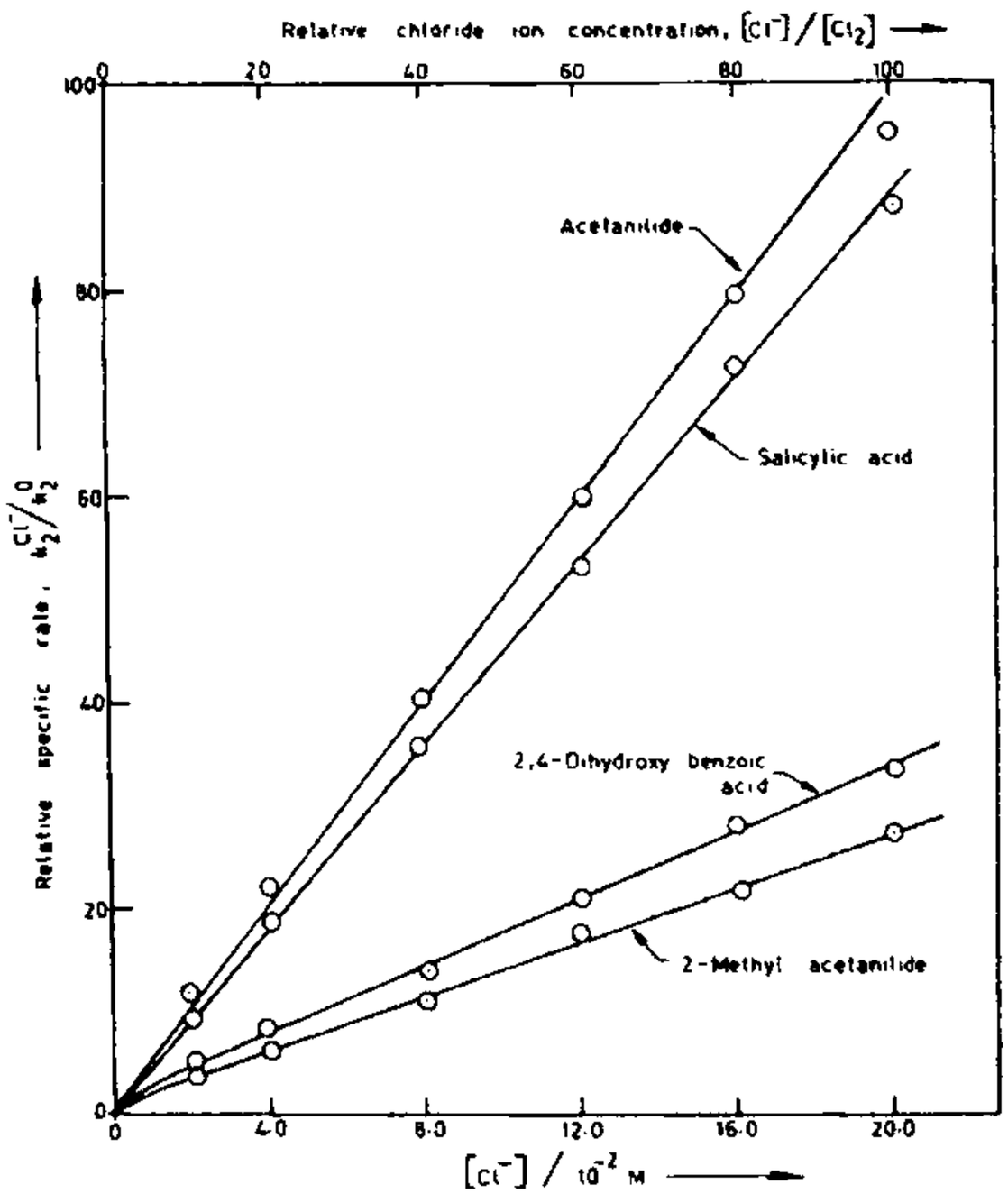


**Figure 1.** Effect of chloride ion on the specific rates of chlorination of aromatic substrates by chlorine in aqueous solution at 25°C.

to a hundred-fold concentration relative to the initial concentration of chlorine, i.e. $[Cl^-]/[Cl_2]$ was varied from 10 to 100 (see table 1 and figure 1). At the final stage the ionic strength of the solution was 0.02 M. The concentration of the chloride ion produced in the reaction was negligible in comparison to that added in these experiments.

The activation energies in the absence of added potassium chloride, and in the presence of a hundred-fold potassium chloride were determined by measuring the specific rates at several temperatures (table 2).

The specific rates were also determined in the presence of a hundred-fold of (i) perchloric acid to determine the effect of suppression of hydrolysis of chlorine, (ii) sodium acetate to investigate into base catalysis, (iii) sodium bicarbonate to confirm the above result and (iv) potassium nitrate, besides that already present as the supporting electrolyte, to examine the possibility of salt effect (table 3).

The kinetics of chlorination and the effect thereon of added chloride ion were similarly studied with 2,4-dihydroxy benzoic acid, acetanilide and 2-methyl acetanilide ( figure 1).

Analysis of the reaction products in both the presence of and absence of added chloride by standard techniques[8,9] showed that salicylic acid and 2,4-dihydroxy acid yielded the respective 5-chloro derivatives while acetanilide and 2-methyl acetanilide yielded 4-chloro derivatives. The other derivatives in all cases were only in traces.

## RESULTS AND DISCUSSION

The results in figure 1 and table 1 clearly show the effect of chloride ion in enhancing many-fold the specific rate. A plot of $k_2^{Cl^-}/k_2^0$, the specific rate in the presence of the chloride ion relative to that in the absence of the added chloride ion versus $[Cl^-]/[Cl_2]$ is linear in every case. The activation energy for chlorination of salicylic acid in the presence of a hundred-fold chloride ion is 24.1 kJ $mol^{-1}$ which is distinctly lower than that in the absence of the added

**Table 2** *Kinetic parameters for the chlorination of salicylic acid by chlorine in aqueous solution at 25.0°C*

| | In the absence of added chloride ion | In the presence of a hundred-fold added chloride ion |
|---|---|---|
| Specific rate/ $M^{-1}\,sec^{-1}$ | 2.00 | 179 |
| Energy of activation /kJ $mol^{-1}$ | 37.7 | 24.1 |
| Entropy of activation /J $K^{-1}\,mol^{-1}$ | −7.01 | −7.45 |
| Frequency factor /$cm^3\,mol^{-1}\,sec^{-1}$ | $6.92 \times 10^9$ | $2.70 \times 10^9$ |

**Table 3** *Effect of various added ions at hundred fold relative concentration on the specific rate of chlorination of salicylic acid by chlorine in aqueous solution at 25.0°C (Specific rate in the absence of added ions: 2.00 $M^{-1}\,sec^{-1}$)*

| Added ion | Chloride | Hydrogen | Acetate | Bicarbonate | Nitrate* |
|---|---|---|---|---|---|
| Specific rate, $k_2^{ion}/M^{-1}\,sec^{-1}$ | 179 | 22.0 | 2.10 | 2.03 | 1.95 |
| $k_2^{ion}/k_2^0$ | 89.5 | 11.0 | 1.05 | 1.01 | 0.975 |

*excluding the potassium nitrate already present as supporting electrolyte.

chloride ion, i.e. 37.7 kJ $mole^{-1}$ (table 2). This strongly indicates that the chloride ion has a catalytic effect on the reaction.

Chlorine in aqueous solution is extensively hydrolyzed to hypochlorous acid, but the latter is

$$Cl_2 + H_2O \rightleftharpoons HClO + H^+ + Cl^-$$

known to be a much slower chlorinating agent than molecular chlorine[10]. Since the hydrolysis equilibrium is established rapidly, the chlorination may be regarded as effectively by molecular chlorine only. The addition of a hundred-fold of $Cl^-$ or $H^+$ should suppress the hydrolysis and hence increase the specific rate to the same extent. Actually the added $H^+$ no doubt increases the specific rate, but the chloride ion increases it much greater. Evidently the chloride ion does more than merely suppress the hydrolysis (table 3).

The formation of trichloride ion $Cl_3^-$ and its electrophilic attack on the aromatic substrate does not seem plausible. For one, $Cl_3^-$, a negatively charged species, would be a much weaker electrophile than $Cl_2$. Secondly, the equilibrium constant $K$ for its formation[11] is only 0.18 at 25.0°C and hence the $[Cl_3^-]$ would be very low at the low $[Cl_2]$ used in this study. Still further, the $[Cl_3^-]$ would be proportional to $K[Cl^-]/1 + K[Cl^-]$ for a given initial concentration of chlorine and hence the $[Cl_3^-]$ would tend to a limiting value at higher concentrations of chloride ion. Therefore if $Cl_3^-$ is the active species, the specific rate should have reached a limiting value at higher concentrations of the chloride ion, but observations are contrary to this expectation.

The chloride ion is a very weak base and yet if it is regarded as a base catalyst, then stronger bases like the acetate and the bicarbonate ions should have enhanced the specific rates significantly. This does not happen (table 3) and hence base catalysis by the chloride ion is improbable.

A hundred-fold relative concentration of potassium nitrate in lieu of the potassium chloride (due to which the ionic strength would be again 0.02 M) does not at all enhance the specific rate. Therefore the possibility of chloride ion enhancing the specific rate by salt effect also is improbable (table 3).

It is thus evident that a different mechanism operates for these chlorinations in the presence of chloride ions. Since the reaction is of the second order, both

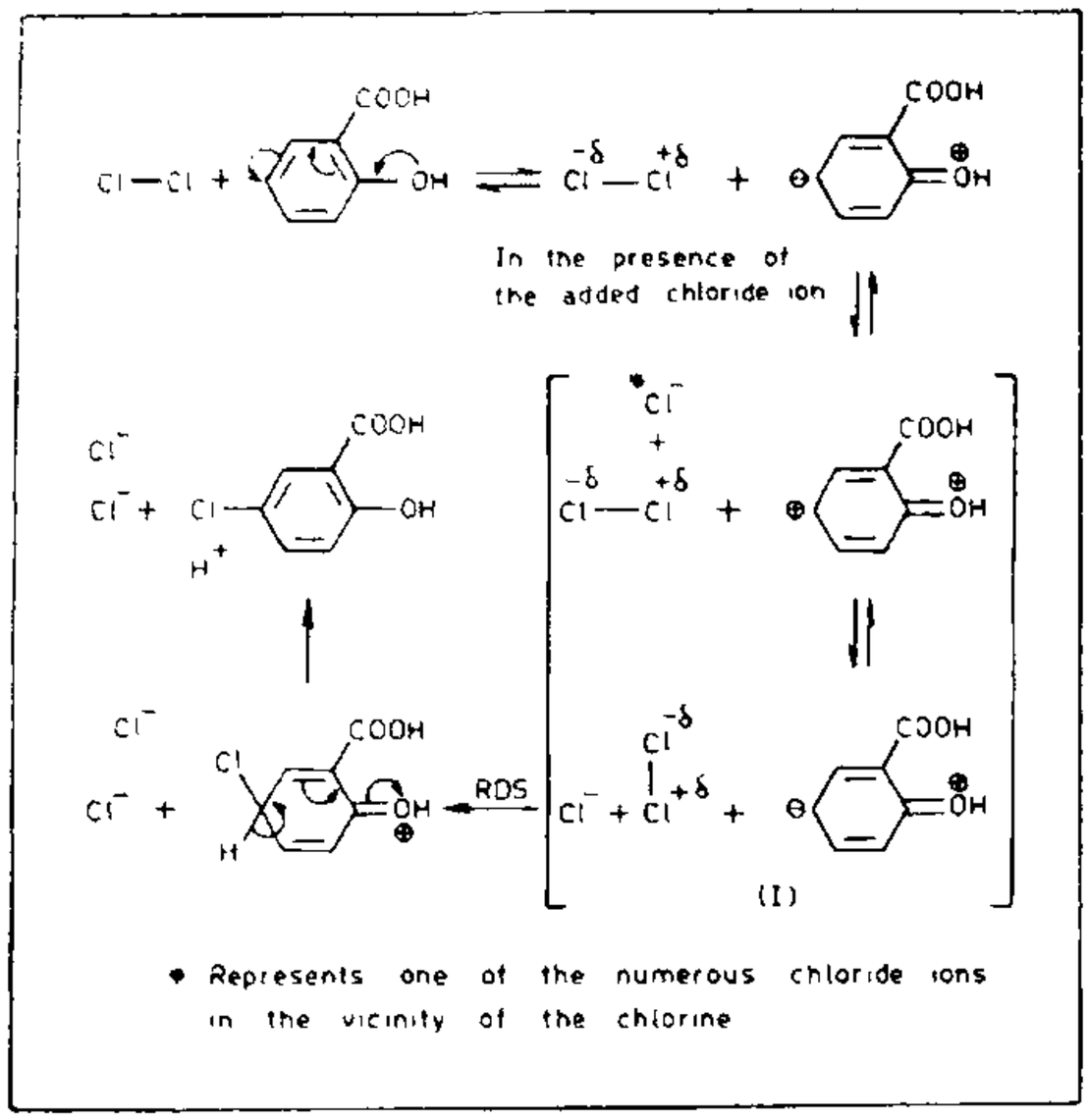


**Figure 2.** Mechanism of the reaction.

chlorine and substrate are involved in the rate-determining step. Further, since the chloride ion catalyzes the reaction, it is also involved in this step. Hence the following mechanism which reasonably explains all the observations is suggested.

The aromatic substrate, with its electron-rich site, polarizes the chlorine molecule. In the presence of a large concentration of added chloride ion, for every chlorine molecule reacting with the substrate, there will be many chloride ions in its near vicinity. Here we postulate that the $\overset{\delta-}{Cl}\text{-}\overset{\delta+}{Cl}$ dipole is stabilized by rearrangement of electrons with any one of these many chloride ions in the vicinity, as shown in (I). This facilitates the electrophilic attack of the Cl-Cl on the aromatic substrate in the rate-determining step. It is well known from studies using chloride ions labelled with radioactive isotope that there is rapid isotope exchange between chloride ion and chlorine[12] in aqueous solution. Since the role of the chloride ion in this mechanism is unique, no other anion is able to stabilize the dipole and catalyze the reaction in a manner as the chloride ion does.

By this mechanism the rate of chloride ion catalyzed chlorination of the substrate $S$ is

$$\text{Rate} = k_3[S]\,[Cl_2]\,[Cl^-].$$

Since whatever chloride ion taking part in the reaction is regenerated, its concentration remains constant and can be incorporated with $k_3$ so that $k_2' = k_3\,[Cl^-]$ and hence

$$\text{Rate} = k_2'\,[S]\,[Cl_2].$$

This explains the second order kinetics of reaction even in the presence of the chloride ion.

The observed reaction rate may be regarded as the sum of the rates of an uncatalyzed reaction and a chloride ion catalyzed reaction:

$$k_2^{Cl^-}[S]\,[Cl_2] = k_2^0[S]\,[Cl_2] + k_3[S]\,[Cl_2]\,[Cl^-]$$

| observed rate | uncatalyzed rate | chloride ion catalyzed rate |
|---|---|---|

and hence, upon dividing throughout by $k_2^0[S]\,[Cl_2]$,

$$k_2^{Cl^-}/k_2^0 = 1 + (k_3[Cl^-]/k_2^0)$$

Therefore a plot of $k_2^{Cl^-}/k_2^0$ versus $[Cl^-]$ should be linear. Further, a plot of $k_2^{Cl^-}/k_2^0$ versus $[Cl^-]/[Cl_2]$ should also be linear, where $[Cl_2]$, the initial concentration of chlorine, is a constant over the entire range of the added chloride ion concentration. Both these expectations are indeed found to be true in every case (figure 1).

It is significant that whereas the activation energy for the reaction in the presence of chloride ion is distinctly lower than that of the reaction in its absence, the activation entropies in the two cases are nearly the same ($\simeq -7\ JK^{-1}\ mol^{-1}$). This indicates the formation of the same intermediate in both cases. The intermediate envisaged in this mechanism is, in fact, identical with the one postulated for electrophilic chlorination by chlorine.

From the various studies to probe into the role of the chloride ion, the mechanism proposed above explains best the remarkable catalytic effect and is consistent with all the observed kinetic features.

26 December 1985

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# NEWS

## EARLY DIAGNOSIS OF CANCER

Research into a new test so sensitive that it may be able to detect cancer at its earliest or pre-cancerous stage is being carried out at Southampton University in Southern England. If successful, it will allow treatment to start before any tumour has developed.

Dr. Andrew Sincock, research scientist in charge of a project investigating the early diagnosis of breast and cervical cancer, has developed a technique for staining sections of tissue with a dye that indicates the amount and age of DNA in cells.

Cancerous and pre-cancerous cells contain large amounts of newly formed DNA, which stains more deeply than the DNA in normal cells. The research is being funded by a voluntary organization known as Quest for Tests for Cancer. Dr Sincock reports that the new method of diagnosis is sensitive enough to pick up even cell-size carcinomas of the breast.

A cervical project is investigating the role of viruses in initiating cervical cancer. It employs DNA profile analysis to quantify virally induced changes in cells.

By using the new technique on exfoliated cells and biopsy specimens still thought to be healthy, it has already been possible to detect changes in breast and cervical cells before actual malignancy has developed. Investigations are now being carried out into detecting cancer of the bowel and lungs at the earliest pre-cancerous stage.

Existing tests, which rely on the appearance of cells, are largely dependent on a human observer identifying what he or she considers to be abnormal. By using the Sincock method, however, it is possible to quantify DNA that would still appear normal to the observer. The possibility of human error is reduced by using a microdensitometer in conjunction with a microcomputer, so that the measurements can be plotted on a visual display and stored for future recall. (*Spectrum* – British Science News, 1986, No. 196/10; British Information Services, British High Command, New Delhi 110028).

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A one week Inter disciplinary course on Electrobiology will be held at the Central Electrochemical Research Institute, Karaikudi 623006, during 10–16 July 1986. This course is intended to highlight the electrochemical principles in biological processes. bioenergetics, biological redox systems, photosynthesis, transmembrane potential, transport through membranes, bioelectromagnetism, electropotential measurement in plants, microbial corrosion, bacterial leaching of metals, electrochemical techniques and methodologies applied to biology and medicine.

Research workers interested/working in the above areas may enrol for this course. The fee is Rs. 500/=. Last date for the receipt of prescribed form of application is 10th June 1986. For further information contact: The Director, Central Electrochemical Research Institute, Karaikudi 623006.