Electronic Interpretation of Organic Reaction Mechanism. VII. Reactions and Structures of Organic Halides in Replacement Reactions

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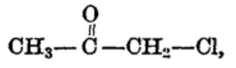
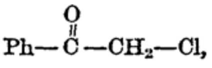
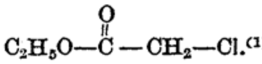
(Received June 2, 1950)

Many of the previous workers who have studied on the SN 2 type reactions indicate that the following compounds show extremely high reactivities toward nucleophilic reagents:

$CH_2=CH-CH_2-Cl$, $PhCH_2-Cl$,


$CH_3-\overset{O}{\overset{\|}{C}}-CH_2-Cl$,


$Ph-\overset{O}{\overset{\|}{C}}-CH_2-Cl$,


$C_2H_5O-\overset{O}{\overset{\|}{C}}-CH_2-Cl$.⑴

In order to study why these compounds are highly reactive in the SN 2 type reactions, an experiment was made by the present authors using the reaction of ionization mechanism (Pull type). For this type of reaction, the organic halides were interacted on silver nitrate in absolute alcohol. As the previous workers⑵ have reported that silver nitrates react with alkyl halide by the ionization mechanism (Pull type) and that it exerts too much catalytic activities in the reaction, the same state was recognized also by the authors. However, since it was found that this catalytic action depended chiefly on the sensitized silver chloride, our experiments with silver nitrate were carried out in a dark room in order to avoid the irregular catalytic action. Our experiments show that allyl chloride and benzyl chloride are much more reactive than the ordinary normal alkyl chloride but that chloroacetone, ω-chloroacetophenone and ethyl chloroacetate do not react so easily as n-butyl chloride does.

In order to find the effect produced by the second or third chlorine atom of these compounds which have two or three chlorine atoms on the same carbon, the authors made the experiments of the reactions of the polychlorides of n-butane and of those of α-polychloroderivatives of toluene with silver nitrate and with potassium iodide. The results indicate that n-butylidene chloride is less reactive than n-butyl chloride in both reactions, *i.e.* with silver nitrate and with potassium iodide, while in the series of benzyl chloride, the reactivities decrease with the increase in number of chlorine atoms on the same carbon atom in the case with potassium iodide and increase with the increase in number of chlorine atoms in the case with silver nitrate.

Experimental

Experimental Procedure :—The temperature of the thermostat used for this kinetic measurements was held within 0.1°. The method of determination used in the reaction with silver nitrate was similar to that used by Burke and Donnan(2a) except the fact that our experiments were performed in sealed tubes in a dark room. A mixture of 5 cc. each of $2N$ alcoholic solutions of organic chloride and silver nitrate was sealed in a 20 cc. test tube and the test tube was immersed in the thermostat as quickly as possible. At regular intervals, the sealed tube was broken and the content was washed into 25 cc. of $0.05N$ solution of NH_4SCN and then this mixture was back titrated with $0.2N$ silver nitrate using iron alum as an indicater. To avoid large catalytic activities produced by silver chloride formed, the reaction was stopped when 30% of the organic chloride had reacted. The velocity constants were obtained from the following equation:

$$k=\frac{1}{t}\left(\frac{1}{C}-\frac{1}{C_0}\right) \qquad (i)$$

where C is the concentration of silver nitrate at time t, while C_0 is the initial concentration of silver nitrate.

For the reaction with potassium iodide in acetone, the authors followed the method described by Conant and his co-workers.(1a) Since this method has been used quite extensively, it is not described here.

Materials :—The solvent used was absolute alcohol which was prepared by boiling dry alcohol with silver nitrate for a few hours. The solution of silver nitrate can be kept in dark without

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(1) (a) Conant, Kirner and Hussey, *J. Am. Chem. Soc.*, **66**, 232 (1924); **47**, 478, 488 (1925).
(b) Clarke, *J. Chem. Soc.*, **97**, 416 (1916).
(c) Wilson, *Chem. Rev.*, **16**, 149 (1935).

(2) (a) Burke and Donnan, *J. Chem. Soc.*, **85**, 555 (1904).
(b) Senter, *J. Chem. Soc.*, **97**, 346 (1916).
(c) Hammett. "Physical Organic Chemistry" Chapter V.

spoiling for a week, but the authors avoided to use the solution which was prepared more than a week before the experiment. At each time the solution was freshly prepared.

Both allyl chloride and benzyl chloride used were the commercial products. *n*-Butylidene chloride and benzal chloride were prepared from the corresponding aldehyde by reacting these with phosphor pentachloride. Benzotrichloride was prepared by the reaction of benzyl chloride with chlorine. Monochloroacetone and ω-chloroacetophenone were prepared by reacting the corresponding ketone with chlorine, *n*-butyl chloride from *n*-butyl alcohol and hydrochloric acid using zinc chloride as a catalyst, and ethyl chloroacetate by the ordinary esterification of chloroacetic acid with ethanol. All these compounds were washed with dilute sodium carbonate solution, dried over calcium chloride and then distilled for sometimes. The boiling points of these compounds are as follows:

$CH_2=CH-CH_2-Cl$	45°
$CH_3-\overset{O}{\overset{\|}{C}}-CH_2-Cl$	119°
$Ph-CH_2-Cl$	179°
$CH_3-CH_2-CH_2-CH_2-Cl$	77.5°
$C_2H_5O-\overset{O}{\overset{\|}{C}}-CH_2-Cl$	143–4°
$Ph-CHCl_2$	88–9° (14 mm.)
$CH_3-CH_2-CH_2CHCl_2$	114–5°
$Ph-\overset{O}{\overset{\|}{C}}-CH_2Cl$	m. p. 56°
$Ph-CCl_3$	104–5° (25 mm.).

Products were investigated in the case of benzyl chloride. Seventeen g. of silver nitrate and 12 g. of benzyl chloride were reacted in 500 cc. absolute alcohol. After filtering the silver chloride precipitated, alcohol was removed by evaporation, thereby leaving some oily substance. Main parts of this oil (15 g.) distilled over at 95–106° under a reduced pressure of 19 mm. This oil gave a deep violet color when treated with diphenylamine and conc. sullfuric acid, which indicated the presence of $-NO_3$ group in the molecule. When this oil was treated with caustic soda, benzaldehyde and benzoic acid were obtained. Benzaldehyde was comfirmed by converting it to 2, 4-dinitrophenylhydrazone, which melted at 131°, and did not show any fall of its melting point when it was mixed with the known sample. Benzoic acid was confirmed by its melting point and mixed melting point with the known. These experiments indicated that the product obtained in this experiment was benzyl nitrate.

Results

The bimolecular velocity constants obtained by the reaction with silver nitrate of *n*-butyl chloride, allyl chloride, benzyl chloride, chloroacetone, ω-chloroacetophenone and ethyl chloroacetate are given in Table 1.

Table 1

Bimolecular Velocity Constants in the Reaction of Organic Chloride with Silver Nitrate in Absolute Alcohol at 50°

Compounds	10^{-5} k at 50°C, l., mol.,$^{-1}$ min.$^{-1}$
$CH_3-CH_2-CH_2-CH_2-Cl$	1.2
$CH_2=CH-CH_2-Cl$	7.9
$Ph-CH_2-Cl$	83.0
$CH_3-\overset{O}{\overset{\|}{C}}-CH_2-Cl$	0.31
$Ph-\overset{O}{\overset{\|}{C}}-CH_2-Cl$	0.67
$C_2H_5O-\overset{O}{\overset{\|}{C}}-CH_2-Cl$	0.32

Bimolecular velocity constants of the reaction with silver nitrate for *n*-butylidene chloride, *n*-butyl chloride, benzyl chloride, benzal chloride, and benzotrichloride are summarized in Table 2.

Table 2

Bimolecular Velocity Constants of the Reaction of Organic Polychlorides with Silver Nitrate in Absolute Alcohol

Compounds	Temp. °C	10^{-5} k, l., mol.,$^{-1}$ min.$^{-1}$
$CH_3-CH_2-CH_2-CH_2-Cl$	50	1.2
$CH_3-CH_2-CH_2-CHCl_2$	50	0.13*
$Ph-CH_2-Cl$	20	8.4
$Ph-CHCl_2$	20	76.7*
$Ph-CCl_3$	20	102.5*

In the case of polychlorides (these with asterisk in Table 2) the observed values of k obtained from the equation (1) were divided by the number of chlorine atome present in the molecule in order to get the velocity constants of the splitting of the first chlorine at the initial step of this reaction; therefore the values with asterisk are all treated accordingly. The reason is that the second and the third step of this reaction are verv fast as compared to the first.

In Table 3, the velocity constants of polychlorides in the reaction with potassium iodide are summarized.

In order to observe the action of silver chloride formed and of sensitized silver chloride, the reactivities in the following three cases were compared: (a) the ordinary reaction between

Table 3

Bimolecular Velocity Constants of Polychlorides in the Reaction with Potassium Iodide in Absolute Acetone

Compounds	Temperature, °C.	k
$CH_3—CH_2—CH_2—CH_2—Cl$	60	0.12
$CH_3—CH_2—CH_2—CHCl_2$	60	0.00
$Ph—CH_2—Cl$	25	0.77
	50	(809)
$Ph—CHCl_2$	50	0.24
$Ph—CCl_3$	50	0.13

silver nitrate and allyl chloride, (b) a reaction of allyl chloride with silver nitrate in the presence of $0.2\,M$ freshly prepared silver chloride, (c) a reaction of allyl chloride with silver nitrate in the presence of $0.2\,M$ sensitized silver chloride. The data obtained are summarized in Table 4.

Table 4

Percentage of Silver Nitrate Reacted with Allyl Chloride after 180 Minutes in the Presence of an Excess of Silver Chloride in Absolute Alcohol

No.	Reactivities, %		
	(a)	(b)	(c)
1	9.08	11.06	13.3
2	9.21	11.07	15.4

Discussion

According to the currently prevailing theory there are two commonly occurring mechanisms for the nucleophilic substitution reactions: one is the bimolecular, kinetically second order substitution (SN 2) (Push type), or "Walden Inversion"(3) and the other is the ionization mechanism (SN 1) (Pull type).(4, 5, 2c) In the SN2 type mechanism, the driving force is chiefly a "Push" or nucleophilic backside attack by the atom or group having an unshared electron pair which is strongly dominant in the bond formation. On the other hand, in the SN 1 type or ionization mechanisms, the main part of the driving force is a "Pull" or front side attack by the solvent or some electrophilic reagent.(6) This weakens the old bond, allowing it to ionize in the rate determining step. This reaction is kinetically of the first order when it is with solvent which exists in large excess. The reaction of alkyl halide with silver nitrate is also the reaction of this type, though it is kinetically second order.

From the standpoint of the tetrahedral constitution of carbon atom, a steric hindrance is caused by the other three groups in the back side of the substituted group, therefore except in more complicated cases,(7) the hindrance must be considered in the SN 2 reaction, but not in the ionization or SN 1 reaction, when the reagent approaches to the reaction center.

There have been many reports concerning the extremely high reactivities of these compounds such as chloroacetone and benzyl chloride in the SN 2 type reaction,(8) and it might be considered from the authors' experiments that the high reactivities of chloroacetone, ω-chloroacetophenone and ethyl chloroacetate in SN 2 type reaction depend upon a low electron density in the α-carbon atom originated by the strong electron attractive effect of carbonyl group, thus making the approach of nucleophilic reagent easier. This interpretation appears to support the electrostatic hypothesis by Hinshelwood, Laidler and Timm.(9) The lower reactivties of these compounds in SN 1 type reaction (Pull-type) are also ascribed to the same reason — a lower electron density on the α-carbon atom, which attracts a pair of electron toward the carbon atom and makes the splitting of the chlorine anion more difficult. This argument is consistent with the hypothesis given by Hughes and Ingold.(10) The high reactivities of allyl chloride and benzyl chloride might be considered as such: as they have highly unsaturated group at α-carbon atoms, there arises the relatively high resonance energy in their transition states of both types of the reactions in common, thus making the ionization of chlorine easier.

The results obtained from the experiments of polychlorides can be well discussed as follows. The decrease of reactivities with the increase in the number of chlorine atoms in the reaction of polychlorides with potassium iodide might be ascribed to the steric hindrance, because the van der Waals' radius of chlorine is much larger than hydrogen. ($Cl=1.8\,Å$, $H=1.2\,Å$, cf., $CH_3=2.0\,Å$).(11) The authors

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(3) (a) Walden, *Ber.*, **28**, 1287 (1875).

(b) Hughes, Juliusburger, Masterman, Topley and Weiss, *J. Chem. Soc.*, **1935**, 1525.

(4) (a) Hughes, Ingold, *Nature*, **132**, 933 (1933).

(b) Hughes, *Trans. Farad. Soc.*, **37**, 602, 612 (1941).

(5) Recently G. Swain indicated that almost all the replacement reactions proceed through concerted mechanism and thereby the meanings of SN 1 or SN 2 have slightly altered out of their original meanings. Swain, *J. Am. Chem. Soc.*, **70**, 1119, 2989 (1948).

(6) Polanyi, *Endeavour*, **8**, 3 (1949).

(7) such as Brown's F-strain.

(8) Branch and Calvin, "Theory of Organic Chemistry", Prentice-Hall, Inc., 1941, pp. 428-440.

(9) Hinshelwood, Laidler and Timm, *J. Chem. Soc.*, **1938**, 848.

(10) Hughes, *J. Chem. Soc.*, **1946**, 968.

(11) Pauling, "The Nature of Chemical Bond", Cornell University Press, 1940, pp. 189.

consider that in the reactions with silver nitrate, the decreasing tendencies of reactivities of the *n*-butyl chloride series and the increasing trends of the benzyl chloride series with the increase in number of chlorine atoms are due to the following reasons. In the series of *n*-butyl chloride, the one chlorine atom, attaching to the simple alkyl group, cannot resonate largely in its transition state, but has the strong attractive inductive effect, thus making difficult the anionic dissociation of the other chlorine atom. On the other hand, in the series of benzyl chloride, chlorine atoms are attached to the carbon atom which can participate in the resonance system with phenyl group, thus making the electrons of the chlorine atoms resonate easily in its transition state. Therefore the one chlorine atom facilitate the ionization of the other chlorine atom, namely the reactivities are increased. Ingold, Hughes and their co-workers also support(12) the fact that in the reactions of alkyl series, the inductive effect is predominant in substitution or elimination, but in the aralphil series, the electromeric effect is prominent factor on their reaction rather than the inductive effect. This is quite in agreement with the results of the authors' experiments.

Summary

(1) It was observed in the reaction of organic chloride with silver nitrate that the irregular catalytic action can be avoided by carrying experiments in a dark room.

(2) Silver nitrate was interacted with several organic chlorides which were highly reactive in SN 2 type reaction and the kinetic data obtained were fully discussed.

(3) Some organic polychlorides were reacted with silver nitrate and with potassium iodide and rates obtained in these reactions were discussed.

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(12) (a) Hughes, Ingold and Taher, *J. Chem. Soc.*, **1940**, 949.

(b) Dhar, Hughes, Ingold, Mondour, Mau and Woolf, *J. Chem. Soc.*, **1948**, 2093.