U.D.C. 547.212; 547.312

Preparation of Vicinal Difunctional Compounds by the Converted Electrophilic Halogenation of Multiple Bonds

L.S.Boguslavskaya

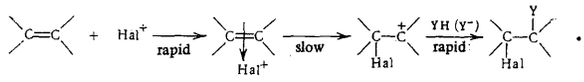
The halogenation of unsaturated compounds in various reactive solvents (water, mineral acids, lower aliphatic alcohols and acids, etc.), involving the addition of halogen and a solvent fragment at the multiple bond, is discussed. The reasons for the varying orientation in the addition of unlike species at the multiple bond, as a function of the structure of the unsaturated compound, the type of electrophilic halogen, and the nucleophile, are considered in terms of the theory of halogenonium ions. The list of references contains 132 items.

CONTENTS

1. Introduction 740
2. Addition of elements of hypohalous acids 740
3. Addition of halogens in organic solvents 742
4. Halogenofluorination 744
5. Mechanism of concerted electrophilic halogenation 745

1. INTRODUCTION

Consideration is given to electrophilic additions to unsaturated compounds, in which the electrophilic species is a positively charged halogen, and the nucleophilic species either a different halogen ion or a neutral molecule. These reactions can be represented by the general scheme



The interest of such processes is that they provide convenient methods for obtaining in a single stage saturated compounds with different substituents in vicinal positions, providing a route to further syntheses. Furthermore, such reactions enable us to establish the sequence of attack by reagents at a double bond and the orientation of the addition of the attacking species to unsymmetrical unsaturated compounds, which makes it possible to assess the mechanism of the processes quite objectively.

Among the immense number of studies on electrophilic addition the least attention has been paid to these reactions[1-4]. The reason is that until recently methods for the quantitative determination of structural isomers were lacking, and therefore great difficulties arose in determining the direction of the addition of unlike species at the double bond in an unsymmetrical unsaturated compound. With the appearance of new methods of analysis (gas–liquid chromatography, nuclear magnetic resonance) interest in concerted additions grew considerably. Several products that had previously been regarded as pure compounds were found to be mixtures of isomers[3].

The selectivity of additions is the most important factor determining the subsequent preparative utilisation of the products. In planning a synthesis it is necessary to know the orientation of addition to be expected from an unsaturated compound of specified structure with a particular electrophilic halogen and nucleophile. Summarising available information on reactions of this type has revealed several of their general features, which can serve as a guide in the development of methods of synthesis. The experimental results have been interpreted in terms of the theory of halogenonium ions[3].

2. ADDITION OF ELEMENTS OF HYPOHALOUS ACIDS

These reactions constitute the most thoroughly studied class of concerted halogenations[3,5]. The hypochlorination of ethylene forms the basis of the hitherto industrially important method of obtaining oxiran via 2-chloroethanol[6]:

$$CH_2{=}CH_2 + Cl_2 + H_2O \rightarrow \underset{85\%}{ClCH_2CH_2OH} + \underset{10\%}{ClCH_2CH_2Cl} + \underset{1\%}{ClCH_2CH_2OCH_2CH_2Cl}\ ,$$

$$ClCH_2CH_2OH \xrightarrow{-HCl} CH_2{-}CH_2 \quad (O)$$

Analogous methods give high yields of propylene chlorohydrin[7], glycerol chlorohydrins from allyl chloride[8], and butylene chlorohydrins from a mixture of butenes[9].

Vinyl chloride adds the elements of hypochlorous acid in conformity with Markovnikov's rule to form the unstable intermediate 1,2-dichloroethanol, which is dehydrochlorinated to give a high yield of chloroacetaldehyde[10]:

$$CH_2{=}CHCl \xrightarrow{HOCl} ClCH_2CH(Cl)OH \xrightarrow{-HCl} \underset{96\%}{ClCH_2CHO}\ .$$

Cyclohexene reacts with an equimolecular quantity of hypochlorous acid in the presence of mercuric oxide in water to give a 70% yield of 2-chlorocyclohexanol[11]. The action of t-butyl hypochlorite on styrene in aqueous acetic acid at room temperature yields 2-chloro-1-phenylethanol, but in the absence of acetic acid the t-butyl ether of this alcohol is obtained[12] (addition products conforming to Markovnikov's rule):

$$C_6H_5CH{=}CH_2 \xrightarrow[H_2O,\ CH_3CO_2H]{t\text{-}BuOCl} \underset{84\%}{C_6H_5CH(OH)CH_2Cl}\ .$$

Diallyl ether reacts with an aqueous solution of bleaching powder to give an almost theoretical yield of 1,7-dichloro-4-oxaheptane-2,6-diol[13]:

$$(CH_2{=}CHCH_2)_2O \xrightarrow{HOCl} [ClCH_2CH(OH)CH_2]_2O\ .$$

$\alpha\beta$-Unsaturated acids (or their esters), nitriles, aldehydes, and ketones containing an unsubstituted hydrogen atom in the α-position relative to the functional group add hypohalous acids predominantly (but not exclusively) with

the halogen becoming attached to the α-carbon atom, and the hydroxyl to the β-carbon atom[14-27]:

$$CH_2{=}CHCO_2H \xrightarrow{HOCl} HOCH_2CHClCO_2H^{15-17}$$

$$CH_3CH{=}CHCO_2H \xrightarrow[74\%]{HOCl} CH_3CH(OH)CHClCO_2H + \underset{26\%}{CH_3CHClCH(OH)CO_2H}{}^{20}$$

$$CH_2{=}CH{-}CN \xrightarrow[79\%]{HOCl} HOCH_2CH(Cl)CN + \underset{21\%}{ClCH_2CH(OH)CN}{}^{27}.$$

The yields in such reactions are usually 40–67%[22-27], but may reach 90–95% in individual cases (e.g. in the hypochlorination of certain β-substituted $\alpha\beta$-unsaturated acids and their salts)[23].

The orientation of addition changes when a methyl substituent is present at the double bond in the α-position with respect to an electron-accepting functional group: the halogen goes mainly to the β-carbon atom and the hydroxyl to the α-carbon atom[23,27]. The yields (%) are respectively

$$\underset{CH_2=CY}{\overset{CH_3}{|}} \xrightarrow{HOCl} \underset{ClCH_2C(OH)Y}{\overset{CH_3}{|}} + \underset{HOCH_2CClY}{\overset{CH_3}{|}}$$

(Y=COOH 90 and 10; Y=$COOC_2H_5$ 70 and 30; Y=CN 58 and 42).

The direction of the addition of hypochlorous acid to hexenoic acids has been studied as a function of the position of the double bond relative to the carboxyl[22]. Hex-2-enoic acid reacts so slowly that a considerable proportion of the hypochlorous acid decomposes, and a single product—2-chloro-3-hydroxyhexanoic acid—is formed in low yield (15%). Hex-3-enoic acid reacts considerably more readily and gives a good yield of a mixture of addition products—3-chlorohexan-4-olide and 4-chloro-3-hydroxyhexanoic acid:

$$CH_3CH_2CH{=}CHCH_2CO_2H \xrightarrow{HOCl} \underset{80\%}{CH_3CH_2CH(O{-}CHClCH_2CO)} + \underset{20\%}{CH_3CH_2CHClCH(OH)CH_2CO_2H}.$$

Hex-4-enoic acid on hypochlorination gives an almost theoretical yield of 5-chlorohexan-4-olide, with a less than 5% yield of the addition product of opposite orientation:

$$CH_3CH{=}CHCH_2CH_2CO_2H \xrightarrow{HOCl} \underset{95\%}{CH_3CHClCH(O{-}CH_2CH_2CO)}.$$

Hypohalous acids add to butadiene preferentially at the 1,2-position[28,29]:

$$CH_2{=}CH{-}CH{=}CH_2 \xrightarrow[H_2O,CH_3CO_2H]{t\text{-}BuOCl} \underset{20\%}{ClCH_2CH(OH){-}CH{=}CH_2} + \underset{14\%}{ClCH_2CH{=}CHCH_2OH}.$$

Aqueous bromoacetamide acts on chloroprene and bromoprene to give 30–35% yields of products exclusively of 3,4-addition[30-32]:

$$CH_2{=}CCl(Br){-}CH{=}CH_2 \xrightarrow{HOBr} CH_2{=}CCl(Br){-}CH(OH)CH_2Br.$$

1-Bromobutadiene and 1,2-dichlorobutadiene also add hypobromous acid at the unsubstituted double bond[32,33]. 1,4-Addition products to halogenated butadienes have not been detected. This was explained by steric hindrance by the halogen substituent to the approach of the attacking electrophilic halogen[34].

Fundamental researches on the addition of hypohalous (hypochlorous, hypobromous, and hypoiodous) acids to unsaturated compounds have been undertaken by the English school of chemists[3]. As will be shown below, the main features discovered in the study of these reactions are of general significance. An immense volume of data have been obtained on the direction of the addition of hypochlorous acid to propene compounds in dilute aqueous solutions of perchloric acid and silver perchlorate (to combine with the chloride anion) in conformity with scheme 1 (Table 1).

Table 1. Products of the hypochlorination of propene derivatives according to scheme 1.

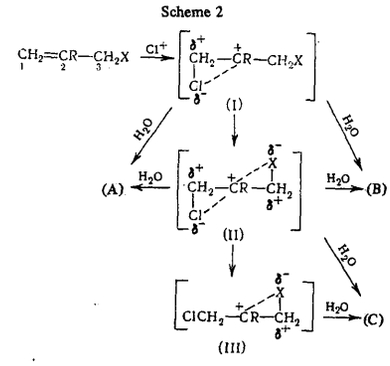
R	X	Products, % (A)	(B)	(C)	Ref.
H	H	91	9	0	15, 36
H	OH	73	27	0	37, 39
H	^{36}Cl	30	66	4	38, 40
H	Br	32	40	28	41
H	I	30	22	48	42
CH_3	H	100	0	0	35
Cl	^{36}Cl	96	4	0	43, 44
CH_3	^{36}Cl	94	4	2	40

The chlorine cation is found to add either at $C_{(1)}$ or at $C_{(2)}$, the selectivity of the reaction depending on the presence of substituents at $C_{(2)}$ and $C_{(3)}$. Migration of halogen from $C_{(3)}$ to $C_{(2)}$ is observed in allyl halides. The percentage of the product of migration increases in the sequence Cl < Br < I; the hydroxy-group at $C_{(3)}$ does not migrate. The presence of methyl or halogen at $C_{(2)}$ favours preferential addition in conformity with Markovnikov's rule.

Scheme 1

$$\underset{1}{CH_2}{=}\underset{2}{C}(R){-}\underset{3}{CH_2}X + HOCl \longrightarrow \underset{\text{(A) according to Markovnikov's rule}}{ClCH_2C(R)(OH)CH_2X} + \underset{\text{(B) contrary to Markovnikov's rule}}{CH_2(OH){-}C(R)ClCH_2X} + \underset{\text{(C) formally contrary to rule (with 3 → 2 migration of substituent X)}}{ClCH_2C(R)(X)CH_2OH}$$

Scheme 2

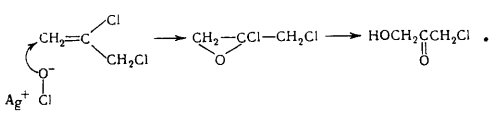


The results suggest a reaction mechanism (scheme 2) in which the chlorine cation, added at the site of highest electron density in the unsaturated compound, forms a chloronium cation (I) by coordination of its lone pairs of electrons with the cationic carbon centre. This stage determines the rate of the reaction. If the substituent X is likewise capable of such coordination, structures (II) and (III) are also possible. Further reaction of these ions

with water yields the adducts (A) (in conformity with Markovnikov's rule), (B) (unrearranged adduct contrary to the rule), and (C) (rearranged adduct contrary to the rule). A methyl group at the cationic carbon centre stabilises the intermediate cation and favours orientation of addition according to rule[35,45,46]: with 3-chloro-2-methylpropene 2% of the 6% of adduct formed contrary to Markovnikov's rule corresponds to the rearranged product (C).[40] A chlorine atom at the cationic carbon centre also promotes orientation according to the rule[43,45], but 3 → 2 migration of the allyl halogen does not occur[43].

Polar solvents stabilise the intermediate carbon cation and thereby promote the 3 → 2 displacement of the allylic halogen. Thus in the hypochlorination of allyl bromide not in water but in a less ionised solvent—40% and 70% aqueous dioxan[41]—the quantity of rearranged adduct has fallen from 28% to 18% and 11% respectively. A similar phenomenon has been observed with allyl iodide[42].

When 2,3-dichloropropene undergoes hypochlorination in the presence of silver perchlorate, the yield of normal addition products (Table 1) decreases, and a new product, 1-chloro-3-hydroxyacetone, appears[44,48,49]. When an alkene labelled with chlorine-36 at position 3 was used, 1-chloro-3-hydroxyacetone was obtained containing all the labelled chlorine. Kinetic measurements in the presence of excess of silver ions and of the alkene showed the occurrence of autocatalysis, which is promoted by increasing the concentration of hypochlorous acid and of the alkene together with low concentrations (preferably the absence) of mineral acid. Analysis of the products under kinetically controlled conditions showed that the autocatalysis was due to the formation of 1-chloro-3-hydroxyacetone. The explanation offered[49] for these results was that, in the presence of silver ions, the usual electrophilic addition was accompanied by nucleophilic attack on the double bond by the hypochlorite anion with subsequent formation of an epoxide. Under the reaction conditions the epoxide ring was opened with formation of the hydroxyketone:



This reaction is favoured by the presence of electron-accepting substituents attached at the double bond.

Orientation contrary to Markovnikov's rule occurs to a greater extent with electrophilic bromine and iodine than with electrophilic chlorine[41,42,50-52] (cf. Table 1):

$$CH_3{=}CH{-}CH_3 \xrightarrow[Cl^-]{Br^+} \underset{54\%}{BrCH_2CHClCH_3} + \underset{46\%}{ClCH_2CHBrCH_3}\ .$$

The presence of strongly electron-donating or electron-accepting groups at the double bond promotes the selective occurrence of concerted addition[50-52]:

$$C_6H_5CH{=}CH_2 \xrightarrow[Cl^-]{I^+} C_6H_5CHClCH_2I \quad (95\%)$$

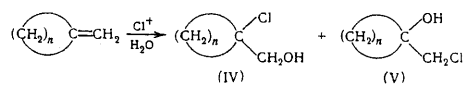
$$CH_3CH{=}CHSO_3H \xrightarrow[Cl^-]{I^+} CH_3CHClCHISO_3H \quad (90\%)\ .$$

The addition of hypobromous acid to 3,3,3-trichloropropene takes place selectively contrary to the rule[53]:

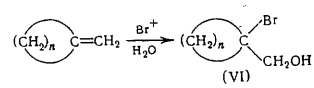
$$CH_2{=}CHCCl_3 \xrightarrow[H_2O]{Br^+} HOCH_2CHBrCCl_3\ .$$

The orientation of addition is similar in the hypochlorination of 3,3-di- and 3,3,3-tri-chloropropenes[54].

The addition of hypochlorous acid to methylenecycloalkanes yields two structural isomers, whereas the addition of hypobromous acid gives almost entirely a single isomer formed contrary to Markovnikov's rule[45,55,56]:



with $n = 4-7$ the respective percentages of (IV) are 60, 41, 67, and 35, accompanied by (V)—40, 50, 32, and 64;



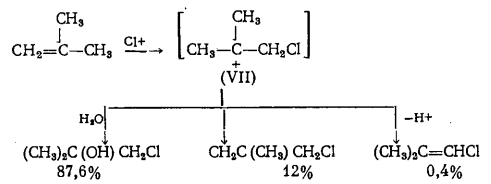
the percentages of (VI) with $n = 4-7$ are respectively 99, 91, 98, and 87. The predominance of the anomalous orientation in the case of the cyclopentane and cycloheptane rings is attributed[55] to steric hindrance of the trigonal carbon atom in these rings, but it is acknowledged that such an explanation does not completely account for the influence of the ring on the orientation in this reaction, since the addition of hydrogen bromide to such compounds yields an adduct strictly according to Markovnikov's rule[57].

When allene hydrocarbons react with an aqueous suspension of calcium hypochlorite in an atmosphere of carbon dioxide, addition takes place with the chlorine cation going to the central carbon atom, and the hydroxyl to the adjacent atom having the largest number of alkyl substituents[58]:

$$CH_2{=}C{=}CH{-}C_2H_5 \xrightarrow[H_2O]{Cl^+} \underset{\substack{OH\\63\%}}{CH_2{=}CClCHC_2H_5} + \underset{\substack{OH\\7\%}}{CH_2CCl{=}CHC_2H_5}\ .$$

In no case was the formation of α-chloro-ketones observed, which should have been obtained with the opposite orientation of addition. An earlier publication[59] had reported that chloroacetone was obtained by the action of hypochlorous acid on allene.

Concerted addition to unsaturated compounds having a quaternary carbon atom at the double bond is accompanied by the formation of small amounts of unsaturated substitution products[4,43,44,46,47]:



Possible reasons why particularly ions of type (VII), having electron-donating substituents at the cationic carbon centre, tend to undergo the competing loss of a proton have been discussed[4,60-62].

3. ADDITION OF HALOGENS IN ORGANIC SOLVENTS

The reaction of unsaturated compounds with molecular halogens, *N*-halogeno-amides, or t-butyl hypochlorite in certain organic solvents (alcohols, acids, acid anhydrides) or mineral acids (sulphuric, phosphoric, etc.) results in concerted addition of halogen and a solvent fragment at the multiple bond. Comprehensive investigations on the halogenoalkoxylation of ethylenic, diene, and enyne hydrocarbons and the properties of the resulting ethers of β-halogeno-alcohols have been reported in detail in a monograph[63].

When ethylene and chlorine are passed simultaneously into a solution of sodium acetate in acetic acid, a mixture of dichloroethane and 2-chloroethyl acetate is obtained[64]:

$$CH_2=CH_2 \xrightarrow[CH_3CO_2H.\,CH_3CO_2Na]{Cl_2} \underset{47\%}{ClCH_2CH_2OCOCH_3} + \underset{45\%}{ClCH_2CH_2Cl}\ .$$

Conducting this reaction in acetic anhydride increases the yield of the chloro-ester to 87%. The use of methyl acetate as solvent raises the yield of dichloroethane. Chlorination (or bromination) of ethylene in the presence of mercuric acetate in formic, acetic, and chloroacetic acids also leads to the formation of 2-halogenoalkyl esters[65].

The action of *NN*-dichlorobenzenesulphonamide in methanol on but-2-ene gives 2-chloro-3-methoxybutane together with a small quantity of 2,3-dichlorobutane[66]:

$$CH_3CH=CHCH_3 \xrightarrow[CH_3OH]{Cl+} \underset{70-80\%}{CH_3CHClCH(OCH_3)CH_3} + CH_3CHClCHClCH_3\ .$$

The same reaction with but-1-ene probably leads to a mixture of isomers with the substituents in the 1,2-positions[66,67].

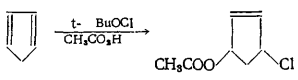
t-Butyl hypochlorite acts on alkenes (ethylene, propene, pent-2-ene, hex-3-ene, hept-1-ene, cyclohexene) in methanol, ethanol, phenol, and acetic acid in the presence of catalytic quantities of toluene-*p*-sulphonic acid to give satisfactory yields (from 30–40% to 60–70%) of the corresponding β-chlorinated ethers and esters[68]. It must be supposed that, in the case of unsymmetrical alkenes, the products are mixtures of isomers. The preparation of β-halogeno-esters of strong acids by the concerted halogenation of alkenes in these acids has been reported[69,70].

The addition of methyl hypochlorite to buta-1,3-diene by the action of *NN*-dichlorobenzenesulphonamide in methanol gives a total yield of 46% of 1,2- and 1,4-addition products, in which the former strongly predominates[71]:

$$CH_2=CH-CH=CH_2 \xrightarrow{ClOCH_3} \underset{OCH_3\quad 83\%}{ClCH_2CH-CH=CH_2} + \underset{17\%}{ClCH_2CH=CHCH_2OCH_3}\ .$$

The bromo- and iodo-alkoxylation of butadiene yields almost exclusively 1,2-addition products[28,71-73]. Thus the action of a methanolic solution of bromine on butadiene forms 4-bromo-3-methoxybut-1-ene (63%) slightly contaminated with 1-bromo-4-methoxybut-2-ene (4%) and products of the addition of two bromine atoms[73].

The chloro-acetoxylation of cyclopentadiene by the action of t-butyl hypochlorite dissolved in acetic acid gives a 47% yield of a conjugate 1,4-addition product—*trans*-5-chlorocyclopenten-3-yl acetate[74]:



The chloro- and bromo-methoxylation of isoprene always involves the attachment of halogen at position 1. In the case of chloro-alkoxylation this leads to 1,2- and 1,4-addition products in the proportions 2 : 1:[75,76]

$$\overset{1}{CH_2}=\overset{2}{C}(CH_3)-\overset{3}{CH}=\overset{4}{CH_2} \xrightarrow{ClOR} \underset{OR}{ClCH_2\overset{|}{C}(CH_3)-CH=CH_2} + \underset{CH_3}{ClCH_2\overset{|}{C}=CH-CH_2OR}\ .$$

Only 1,2-addition products—3-alkoxy-4-bromo-3-methylbut-1-enes—have been identified on bromo-alkoxylation[63,75]. The bromo- and iodo-alkoxylation of chloroprene and bromoprene, unlike those of isoprene, take place mainly at the 3,4-positions[77-79]:

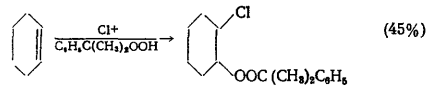
$$\overset{1}{CH_2}=\overset{2}{C}(Cl)-\overset{3}{CH}=\overset{4}{CH_2} \xrightarrow{BrOR} CH_2=\underset{Cl}{C}-\underset{OR}{CH}-CH_2Br$$

The chloro-alkoxylation of the same compounds yields 1,4- and 3,4-addition products in the proportions 4 : 1.[80] Thus in isoprene the substituted double bond is the more reactive, whereas in halogenoprenes this applies to the unsubstituted double bond.

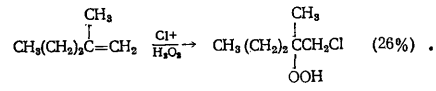
The halogeno-alkoxylation of butenyne and its homologues takes place mainly in the vinyl group[81,82]:

$$CH_2=CH-C\equiv CH \xrightarrow{HalOR} \underset{OR}{HalCH_2-CH-C\equiv CH}\ .$$

The action of t-butyl hypochlorite and alkyl hydroperoxides or hydrogen peroxide on certain ethylenic compounds (2-methylpent-1-ene, hex-3-ene, cyclohexene, etc.) forms β-chlorinated peroxides in 20–50% yields[83]:



(45%),

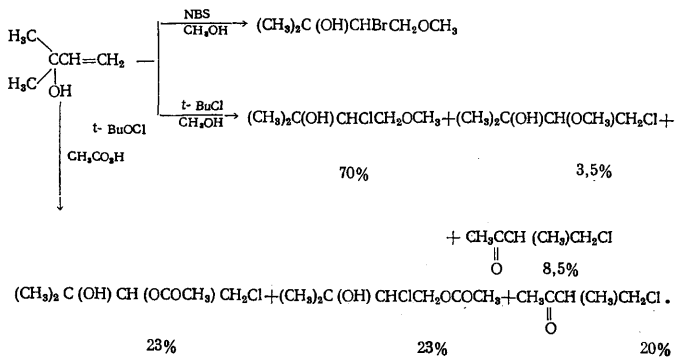


(26%).

Vinyl ethers react with t-butyl hypochlorite in the presence of primary or secondary alcohols, alkyl hydroperoxides, or hydrogen peroxide to give moderate yields of chlorinated acetals, peroxy-acetals, and hydroperoxy-acetals respectively[83].

The chloro-methoxylation of allyl alcohol with methanolic molecular chlorine[84] or hexachloromelamine[85] yields a mixture of isomeric methoxychloropropanols together with 2,3-dichloropropan-1-ol. The addition product conforming to Markovnikov's rule predominates in the isomeric mixture.

The bromo-methoxylation of 1,1-dimethylpropanol with methanolic *N*-bromosuccinimide (NBS)[86] gives a 46% yield of the non-Markovnikov selective addition product. The chloro-methoxylation of this compound with t-butyl hypochlorite in methanol[86] gives a mixture of structural isomers with the same isomer strongly predominating. The addition of chlorine acetate $ClOCOCH_3$ gives a mixture of equal quantities of structural isomers, accompanied by β-chloro-ketones resulting from a pinacoline type of rearrangement[87]:



The chloro- and bromo-methoxylation of 1,1,2-trimethylpropenol also gives a mixture of the two isomeric addition products, together with considerable quantities of β-halogeno-ketones[87-92]. Rearrangement with the formation of β-halogeno-ketones becomes the main reaction of this propenol and of 1-aryl-1,2-dimethylpropenols with t-butyl hypochlorite when protic are replaced by aprotic solvents (dichloromethane, nitromethane)[93-97].

3,3,3-Trifluoropropene reacts readily with an acetic-acid solution of bromine in the presence of mercuric acetate or sulphate to give a high (78%) yield of the non-Markovnikov concerted addition product[98]:

$$CF_3CH{=}CH_2 \xrightarrow[CH_3CO_2H,\,Hg(OCOCH_3)_2]{Br^+} CF_3CHBrCH_2OCOCH_3 .$$

The dibromide is the main product in the absence of mercury salts. An analogous orientation of electrophilic addition is found in the concerted chlorination of 3,3,3-trichloropropene[99] and 3,3,3-trichloro-2-methylpropene[100].

The chlorination of compounds containing a 2,2-dichlorovinyl group, in mixtures of acetic acid and mercuric acetate, formic and concentrated sulphuric acids, gives high yields of α-chlorinated carboxylic acids[101]:

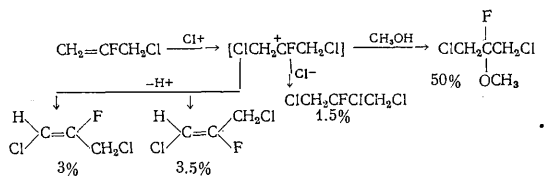
$$R(CH_2)_n CH{=}CCl_2 \xrightarrow[HCO_2H]{Cl^+} [R(CH_2)_n CHClCCl_2OCOH] \xrightarrow[(60-80\%)]{H_2O} R(CH_2)_n CHClCO_2H .$$

Thus the presence of three fluorine or chlorine atoms in the allyl position promotes non-Markovnikov addition. The presence of two halogen atoms in the 1-vinyl position favours the addition of halogen at the adjacent carbon atom forming the double bond[98,101].

Allyl chloride and bromide with methyl hypochlorite form every possible addition product, with the non-Markovnikov products predominating[102]: e.g.

$$CH_2{=}CHCH_2Cl \xrightarrow[CH_3OH]{Cl^+} \underset{12.5\%}{ClCH_2CH(OCH_3)CH_2Cl} + \underset{18.5\%}{CH_3OCH_2CHClCH_2Cl} .$$

The chloro-methoxylation of 2-halogenoallyl chlorides conforms to Markovnikov's rule[103], as was to be expected by analogy with the hypochlorination of 2-chloroallyl chloride[43,44]; unsaturated substitution products are also formed:



The concerted halogenation of double bonds in cholesterol[104,105] and in corticosteroids[106] provides an example of selective addition contrary to Markovnikov's rule.

4. HALOGENOFLUORINATION

In 1959 the first papers were published on the concerted halogeno-fluorination of steroids by *N*-halogeno-amides and anhydrous hydrogen fluoride in the presence of organic acceptors of protons (alcohols or ethers) in chloroform[107–110]. The bromo-fluorination of Δ^5-steroids with *N*-bromoacetamide and hydrogen fluoride forms 5α-bromo-6β-fluorosteroids (contrary to Markovnikov's rule), whereas iodo-fluorination with *N*-iodosuccinimide and hydrogen fluoride gives 5α-fluoro-6β-iodosteroids[110]. Halogeno-fluorination involves *trans*-addition[106,108,109]. Thus vicinal *trans*-bromofluoro- and *trans*-fluoroiodo-cyclohexanes are obtained in satisfactory yields from cyclohexene under the above conditions[109].

This method has since been used to prepare simpler bromofluoro- and chlorofluoro-derivatives. The bromo-fluorination of esters of $\alpha\beta$-unsaturated carboxylic acids unsubstituted in the α-position gives 50–70% yields of 2-bromo-3-fluoroalkanoic esters[111,112]:

$$CH_2{=}CHCO_2CH_3 \xrightarrow[F^-]{Br^+} FCH_2CHBrCO_2CH_3 .$$

The chloro-fluorination of ethylene, propene, vinylidene chloride and fluoride, and methyl acrylate has been accomplished with moderate (30–60%) yields by chlorinating these compounds with gaseous chlorine in liquid hydrogen fluoride or with hexachloromelamine and hydrogen fluoride in ether[113]: e.g.

$$CH_2{=}CHCO_2CH_3 \xrightarrow[F^-]{Cl^+} FCH_2CHClCO_2CH_3 .$$

The intermediate formation of a β-chloro-cation in the concerted addition of chlorine and fluorine to alkenes has been proved[113] in the case of the chloro-fluorination of ethylene in the presence of benzene. Formation of 1-chloro-2-fluoroethane and mono- and dichlorobenzenes is then accompanied by an 8% yield of phenethyl chloride:

$$CH_2{=}CH_2 \xrightarrow{Cl^+} [ClCH_2\overset{+}{C}H_2] \begin{cases} \xrightarrow{F^-} ClCH_2CH_2F , \\ \xrightarrow{C_6H_6} ClCH_2CH_2C_6H_5 . \end{cases}$$

The bromo-fluorination of C_2–C_{18} alk-1-enes by means of *N*-bromoacetamide and hydrogen fluoride in an ether–chloroform mixture gives good (up to 60–70%) yields of 1-bromo-2-fluoroalkanes, together with a certain amount (3–8%) of the isomeric 2-bromo-1-fluoroalkanes[114]. In some cases the addition of pyridine to the solvent increases the yield of the addition product. Thus the bromo-fluorination of styrene in ether produces a 25% yield of β-bromo-α-fluoroethylbenzene, but in a 4 : 1 ether–pyridine mixture the yield rises to 68%. The bromo-fluorination of allyl bromide gives both isomeric dibromofluoropropanes, with the addition product contrary to Markovnikov's rule predominating:

$$CH_2{=}CHCH_2Br \xrightarrow[F^-]{Br^+} \underset{22\%}{BrCH_2CHFCH_2Br} + \underset{32\%}{FCH_2CHBrCH_2Br} .$$

When methyl acrylate undergoes bromo-fluorination by the above method in ethereal pyridine, the expected methyl α-bromo-β-fluoropropionate is accompanied by small quantities of methyl β-bromo-α-fluoropropionate and methyl β-bromo-α-ethoxypropionate[112]. The bromo-fluorination of methyl methacrylate yields the single addition product—methyl β-bromo-α-fluoro-α-methylpropionate[115]:

$$CH_2{=}C(CH_3)CO_2CH_3 \xrightarrow[F^-]{Br^+} BrCH_2\overset{CH_3}{\overset{|}{C}}FCO_2CH_3 .$$

The chloro-fluorination of methyl α-methoxyacrylate by hexachloromelamine and hydrogen fluoride goes similarly[116].

The bromo-fluorination of allyl acetate by means of *N*-bromoacetamide and hydrogen fluoride gives 3-bromo-2-fluoropropyl acetate in low yield. The presence of the isomeric product formed contrary to Markovnikov's rule was not established[115].

The chloro-fluorination of allyl alcohol by hexachloromelamine and hydrogen fluoride in methanolic chloroform yields both possible isomers[85]:

$$CH_2{=}CHCH_2OH \xrightarrow[F^-]{Cl^+} \underset{45\%}{ClCH_2CHFCH_2OH} + \underset{5\%}{FCH_2CHClCH_2OH} .$$

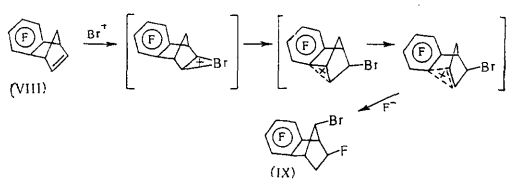
The chloro-fluorination of 2-fluoro- and 2-chloro-allyl alcohols, as well as that of the corresponding chlorides, leads to selective addition of chlorine fluoride in conformity with the Markovnikov rule[103,117]:

$$CH_2{=}CHalCH_2OH \xrightarrow[F^-]{Cl^+} ClCH_2CFHalCH_2OH$$

Hal=F (yield 76%), Cl (50%) .

In the case of the allyl chlorides this is accompanied by small quantities of products of substitution and of the addition of two chlorine atoms[103]. Allyl chloride and bromide are chloro-fluorinated with the formation of every possible addition product; in the case of allyl bromide a product is also detected in which the bromine atom has migrated. Products of substitution by chlorine were not found[102].

Several specific aspects of the addition to fluoroalkenes of interhalogen compounds, and in particular of halogens, have been discussed in review papers[118,119]. The bromofluorination of (VIII) by *N*-bromosuccinimide and hydrogen fluoride in ether yields the Wagner–Meerwein rearrangement product (IX):



(VIII) (IX)

Rearrangement takes place also on the addition of bromine chloride and methyl hypochlorite to (VIII); the addition of iodine chloride, however, is not accompanied by rearrangement[120].

5. MECHANISM OF CONCERTED ELECTROPHILIC HALOGENATION

Examination of the experimental work surveyed in Sections 1–3 shows that the observed orientation of concerted addition at a multiple bond can in most cases be explained satisfactorily by scheme 2 (Section 2). Summarising the experimental results on various reactions involving the concerted electrophilic chlorination of allylic systems makes it possible to elucidate the influence of the nucleophile and the structure of the original unsaturated compound on the orientation of addition.

When position 2 in the initial alkene is unsubstituted, addition of a nucleophile Y is preceded by an intermediate halogenonium cation, the structure of which (I–III in scheme 2) is influenced by neighbouring groups (in particular the substituent X in the compounds surveyed in Table 2).

Attack by the nucleophile Y on the cations results in the formation of—(A) a product of addition according to Markovnikov's rule, (B) an unrearranged product of addition contrary to this rule, and (C) a rearranged product of addition contrary to the rule. When X = H addition both of hypochlorous acid and of chlorine fluoride takes place almost entirely according to rule. When X = OH, Cl, Br, the quantity of anomalous products (B) + (C) increases with increase in the relative participation of the groups X in the formation of onium structures of types (II) and (III). This regularity is observed with all three reactions examined (hypochlorination, chloro-methoxylation, and chloro-fluorination).

In comparison with methanol and water molecules, the fluoride anion, acting as a nucleophile, enhances the selectivity of addition in favour of the adduct (A). This is probably due to the high nucleophilic activity and small size of the fluoride anion, as a consequence of which it is less subject to steric hindrance than are neutral methanol and water molecules, and easily penetrates the shielded cationic carbon centre situated at the central carbon atom.

Nevertheless, in the presence of bulky electronegative substituents (Cl, Br) the proportional attack by the fluoride anion at the less hindered 1-carbon atom (cations I and II) and the 3-carbon atom (cations II and III) increases, and the relative quantity of non-Markovnikov adducts becomes larger. It is noteworthy that the ratio of rearranged to unrearranged adduct is considerably larger in the chloro-fluorination than in the hypochlorination of allyl bromide (C/B = 1.6 and 0.7), which is probably due to the higher polarity of the environment produced by liquid hydrogen fluoride. When the nucleophiles are bulky and possess less nucleophilic activity than methanol and water molecules, attack on the intermediate cation is more intense at the less hindered 1,3-carbon atoms. For these nucleophiles with X = Cl, Br the non-Markovnikov isomers predominate.

Table 2. Concerted electrophilic chlorination of allylic derivatives according to scheme 2:

$$CH_2{=}CHCH_2X + Cl^+ + Y \rightarrow (A) + (B) + (C)$$

X	Y	Products, % (A)	(B)	(C)	Ref.
H	H_2O	91	9	0	35–37
H	F^-	100	—	—	113
OH	H_2O	73	27	0	39
OH	CH_3OH	71	29	0	102
OH	F^-	90	10	0	84, 102
^{36}Cl	H_2O	30	66	4	38, 40
Cl	CH_3OH	41	—	59*	85, 102
Cl	F^-	68	—	32*	102
Br	H_2O	32	40	28	41
Br	CH_3OH	26	—	74*	102
Br	F^-	60	15	25	102

* Sum of (B) + (C).

These ideas suggest that passing from allyl alcohol to the acetate and especially the trihalogenoacetates will produce a change in the orientation of concerted addition in favour of the non-Markovnikov adduct. The expected effect has in fact been observed[121] in the chloro-fluorination and chloro-methoxylation of these derivatives (Table 3). For the addition of chlorine fluoride the relative quantity of the non-Markovnikov adduct 2-chloro-3-fluoropropan-1-ol increases in the sequence

$$OH < OCOCH_3 < OCOCCl_3 < OCOCF_3,$$

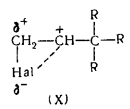
for the addition of methyl hypochlorite the quantity of the corresponding adduct 2-chloro-3-methoxypropan-1-ol increases in the sequence

$$OH < OCOCH_3 < OCOCF_3 < OCOCCl_3.$$

This fact is consistent with the concept of steric hindrance to attack by the nucleophile. The bulky trichloroacetate group proves a greater obstacle than the trifluoroacetate group to the electrically neutral nucleophilic methanol molecule. The small, negatively charged fluoride ion is probably more subject to electrostatic repulsion than to actual steric hindrance, so that the trifluoroacetate group then exerts a stronger orienting influence than does the trichloroacetate group.

It is probable that the role of steric factors is in general large in electrophilic halogenation. This principle is illustrated by the preferential non-Markovnikov halogenation of propene derivatives in which all the allylic hydrogen

atoms have been replaced by other groups— $CH_2:CH.C(CH_3)_3$,[122] $CH_2:CH.CCl_3$,[53,54] $CH_2:CH.CF_3$,[98] and $CH_2:CH.COOR$.[111-113] These results cannot be explained solely by the distribution of electron density in the ground state of the unsaturated compounds, for otherwise the opposite orientation would have been expected with t-butylethylene (n-butylethylene gives 80% of the Markovnikov addition product[122]). It must be assumed that the most important factor here is the shielding effect of β-substituents, which block the cationic carbon centre in the ion



(X)

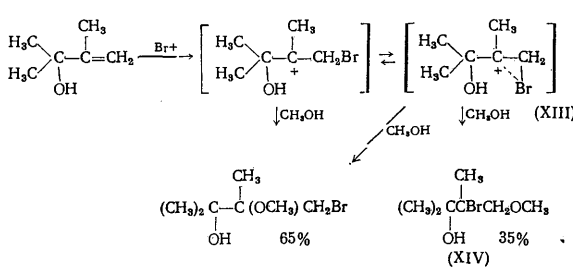
leaving the terminal carbon atom more accessible to attack by the nucleophile[122,123].

Table 3. Concerted chlorination of allyl acetates[121].

Initial compound	Addition products, %	
	according to Markovnikov	contrary to Markovnikov
Chloro-fluorination	$ClCH_2CHFCH_2OH$	$FCH_2CHClCH_2OH$
$CH_2=CHCH_2OH$	90	10
$CH_2=CHCH_2OCOCH_3$	82	18
$CH_2=CHCH_2OCOCCl_3$	74	26
$CH_2=CHCH_2OCOCF_3$	67	33
Chloro-methoxylation	$ClCH_2CH(OCH_3)CH_2OH$	$CH_3OCH_2CHClCH_2OH$
$CH_2=CHCH_2OH$	71	29
$CH_2=CHCH_2OCOCH_3$	54	46
$CH_2=CHCH_2OCOCCl_3$	36	64
$CH_2=CHCH_2OCOCF_3$	50	50

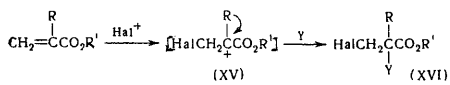
The concerted chlorination of 2-methyl- and 2-halogeno-allyl compounds takes place almost entirely according to Markovnikov's rule (Table 4). With an electron-donating substituent (α-substituent) present in the resulting cationic carbon centre, both addition of the nucleophile and detachment of a proton are probably preceded by a classic carbonium ion (XI) [scheme 3]. The decrease in the positive charge in the cationic carbon centre due to the electron-donating influence of the substituent R prevents formation of the halogenonium cation (XII) by coordination of the p-electrons of the β-halogen (this applies mainly to chlorine, which interacts feebly with the cationic carbon centre[3]). However, the intermediate state (XII) is not excluded in chlorination, since small quantities (4–6%) of non-Markovnikov adducts are nevertheless formed (Table 4 and also Refs. 84–89).

In the concerted bromination of 1,1,2-trimethylpropenol the equilibrium is already considerably displaced towards the halogenonium ion (XIII), and the quantity of non-Markovnikov adduct (XIV) is large[87-89]:



(XIV)

In this case the β-substituents also favour orientation contrary to Markovnikov's rule. The strong orienting influence of α-substituents capable of donating electrons to the cationic carbon centre is apparent in electrophilic addition to α-substituted acrylaldehydes[124] and acrylates[23,115,116], which in the absence of an α-substituent tend to add contrary to the rule[5,15-17,22,23,111-113].



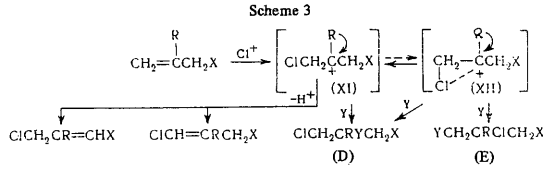
(XV) (XVI)

Table 4. Concerted chlorination of 2-substituted allylic derivatives according to scheme 3:

$CH_2=CRCH_2X+Cl^++Y \rightarrow (D)+(E)$

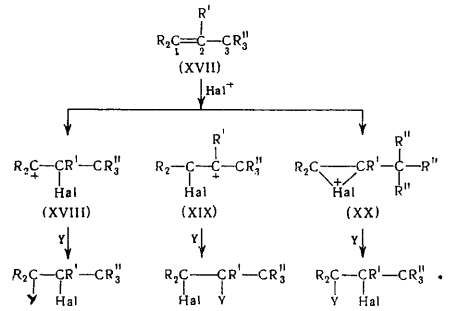
R	X	Y	Products, % (D)	Products, % (E)	Ref.
CH_3	H	H_2O	100	0	35
CH_3	Cl	H_2O	94	6	40
F	OH	F^-	100	0	117
Cl	OH	F^-	100	0	117
F	Cl	CH_3OH	100	0	103
F	Cl	F^-	100	0	103
Cl	Cl	H_2O	96	4	43, 44
Cl	Cl	CH_3OH	>96	<4	103
Cl	Cl	F^-	100	0	103

Scheme 3



The substituents (methyl[14,15,23,115], methoxyl[116,124,125], and probably halogen[126]) enhance the nucleophilic character of the double bond in acrylates and thereby promote formation of a stable carbonium ion (XV) and hence the Markovnikov adduct (XVI). Thus the distribution of electron density in the ground state of the unsaturated molecule is not the dominant factor determining the direction of concerted electrophilic addition[2]. The orientation of addition obviously depends mainly on the structure of the transitional cation, in which an important part is played by the electronic and steric effects of substituents in α- and β-positions relative to the cationic carbon centre[3,61,102,103].

Let us consider as unsaturated compound the propene system (XVII) (in which R and R′ are substituents capable of donating electrons to the cationic carbon centre). Three main types of intermediate carbon cations (XVIII)–(XX) may be formed as a result of electrophilic attack by the halogen:



The presence of 1-vinyl substituents R favours formation of the stable classic ion (XVIII) and hence addition of halogen to $C_{(2)}$ while the nucleophile Y goes to $C_{(1)}$. The presence of a 2-vinyl substituent R′ favours the classic ion (XIX) with addition of halogen to $C_{(1)}$ and the nucleophile Y to $C_{(2)}$. Allylic substituents R″ shield the central carbon atom in the cation (XX) and promote attack by the nucleophile at $C_{(1)}$ with addition of halogen at $C_{(2)}$†. Which addition product predominates depends also on the nucleophilic activity and the steric radius of the attacking reagent Y. This effect is most strongly developed when R = R″ = H, i.e. when an intermediate cation of halogenonium type (XX) is dominant.

In the simple cases discussed above we observe selective addition either according or contrary to Markovnikov's rule. There are other views on the mechanism of the electrophilic halogenation of unsaturated compounds, developed by Shilov[127-131], which envisage the formation of a different type of donor–acceptor complexes of the substrate with the attacking molecules. However, the suggested schemes cannot explain the varying orientation of the addition of unlike species at a double bond, nor the rearrangement usually observed in such reactions.

Theoretical aspects of the electrophilic halogenation of diene hydrocarbons with conjugated multiple bonds have been considered[3,72,132]. There is insufficient clarity in this question[3,132], and the problem requires further study.

REFERENCES

1. C. K. Ingold, "Structure and Mechanism in Organic Chemistry" (Translated into Russian), Inostr. Lit., Moscow, 1959, p. 520.
2. H. Becker, "Einführung in die Elektronentheorie organisch-chemischer Reaktionen" (Translated into Russian), Mir, Moscow, 1965, pp. 367–387.
3. P. B. D. de la Mare and R. Bolton, "Electrophilic Additions to Unsaturated Systems" (Translated into Russian), Mir, Moscow, 1968, pp. 110–123, 126–130, and 277–284.
4. I. V. Bodrikov and E. S. Smolyan, Uspekhi Khim., 35, 853 (1966) [Russ. Chem. Rev., No. 5 (1966)].
5. Houben-Weil, "Methoden der organischen Chemie", Vol. 5/3, 769–780 (1962).
6. "Okis' Etilena" (Oxiran), Khimiya, 1967, 8, p. 167.
7. F. Ferrero, L. P. Flamme, and M. Fourer, Ind. chim. belge, 19, 113 (1954).
8. H. Essex and A. L. Ward, US P. 1 534 879 (1919); Chem. Abs., 20, 3171 (1926).
9. H. Wegheffer, BRD P. 804 562 (1948); Chem. Zentr., II, 1508 (1951).
10. H. P. A. Groll and G. Hearne, US P. 2 060 303 (1934); Chem. Zentr., I, 4154 (1937).
11. Org. Synth., 1, 158 (1932).
12. W. E. Hanby and H. N. Rydon, J. Chem. Soc., 114 (1946).
13. H. Wittcoff, J. R. Roach, and S. E. Miller, J. Amer. Chem. Soc., 71, 2666 (1949).
14. "Encyclopedia of Polymer Science and Technology", John Wiley and Sons Inc., New York, 1, 268 (1965).
15. P. Vaculík, "Chemie Monomeru" (Translated into Russian), Inostr. Lit., Moscow, 1960, p. 408.
16. R. Melikoff, Ber., 12, 2227 (1879).
17. P. Melikoff, Ber., 13, 2153 (1880).
18. P. Melikoff, Ber., 15, 2586 (1882).
19. P. Melikoff, Ber., 16, 1268 (1883).
20. P. Melikoff, Annalen, 234, 197 (1886).
21. P. Melikoff, Annalen, 266, 358 (1891).
22. G. F. Bloomfield and E. H. Farmer, J. Chem. Soc., 2062 (1932).
23. G. F. Bloomfield, E. H. Farmer, and G. B. Hose, J. Chem. Soc., 800 (1933).
24. G. A. Ropp, W. C. Craig, and V. Raaen, Org. Synth., 33, 15 (1953).
25. G. Hesse and H. Stahl, Chem. Ber., 89, 2424 (1956).
26. A. Ya. Yakubovich, N. A. Bogoslovskii, E. A. Pravova, I. N. Belyaev, and V. V. Razumovskii, Zhur. Obshch. Khim., 30, 2496 (1960).
27. V. I. Kondratenko, B. A. Geller, and I. G. Khaskin, Zhur. Org. Khim., 7, 1343 (1971).
28. A. A. Petrov, Uspekhi Khim., 22, 905 (1953).
29. R. M. Evans and L. N. Owen, J. Chem. Soc., 239 (1949).
30. A. A. Petrov, Zhur. Obshch. Khim., 10, 1013 (1940).
31. A. A. Petrov, Zhur. Obshch. Khim., 9, 2232 (1939).
32. A. A. Petrov, Uspekhi Khim., 13, 203 (1944).
33. A. A. Petrov, Zhur. Obshch. Khim., 13, 230 (1943).
34. A. A. Petrov, Dokl. Akad. Nauk SSSR, 78, 63 (1951).
35. P. B. D. de la Mare and A. Salama, J. Chem. Soc., 337 (1956).
36. M. S. Kharasch, S. C. Klieger, and F. R. Mayo, J. Org. Chem., 4, 428 (1939).
37. L. Smith and S. Skyle, Acta Chem. Scand., 4, 39 (1950).
38. P. B. D. de la Mare and J. J. Pritchard, J. Chem. Soc., 3990 (1954).
39. P. B. D. de la Mare and J. J. Pritchard, J. Chem. Soc., 3910 (1954).
40. P. Bollinger and P. B. D. de la Mare, J. Chem. Soc., 1481 (1957).
41. P. B. D. de la Mare, P. G. Naylor, and D. L. H. Williams, J. Chem. Soc., 443 (1962).
42. P. B. D. de la Mare, P. G. Naylor, and D. L. H. Williams, J. Chem. Soc., 3429 (1963).
43. P. Bollinger, P. B. D. de la Mare, and D. L. H. Williams, J. Chem. Soc., 2467 (1960).
44. D. L. H. Williams, Chem. and Ind., 1956 (1963).
45. J. C. Traynham and O. S. Pascual, J. Amer. Chem. Soc., 79, 2341 (1957).
46. I. V. Bodrikov, Z. S. Smolyan, V. P. Golendeev, and G. V. Korchagina, Trudy Khim. i Khim. Tekhnol. Gor'kii, No. 3, 494 (1964).
47. D. W. Pearson and D. L. H. Williams, J. Chem. Soc., (B), 436 (1970).
48. L. A. Hopwood and D. L. H. Williams, J. Chem. Soc., (B), 718 (1968).
49. D. L. H. Williams, J. Chem. Soc., (B), 436 (1970).
50. P. B. D. de la Mare and S. Galandauer, J. Chem. Soc., 36 (1958).
51. C. K. Ingold and H. G. Smith, J. Chem. Soc., 2742 (1931).
52. C. K. Ingold and H. G. Smith, J. Chem. Soc., 2752 (1931).
53. A. N. Nesmeyanov, R. Kh. Freidlina, and L. I. Zakharkin, Uspekhi Khim., 25, 666 (1956).
54. J. R. Shelton and L. Lee, J. Org. Chem., 23, 1876 (1958).
55. J. G. Traynham and O. S. Pascual, Tetrahedron, 7, 165 (1959).
56. J. G. Traynham, J. Chem. Educ., 392 (1963).

† We have already mentioned a possible migration of allylic substituents R″ to $C_{(2)}$ when R″ = Cl, Br, I, and also rearrangements of the pinacoline type in the halogenation of vinylalkyl(aryl)carbinols (Sections 2, 3, and 5).

57. J. G. Traynham and O. S. Pascual, J. Org. Chem., 21, 1362 (1956).
58. J. P. Bianchini and M. Cocordano, Tetrahedron, 26, 3401 (1970).
59. E. U. Elam, US P. 2 856 430 (1957); Chem. Abs., 53, 5132 (1952).
60. Z. S. Smolyan, I. V. Bodrikov, and V. P. Golendeev, see Ref. 46, p. 329.
61. I. V. Bodrikov, S. V. Spiridonova, Z. S. Smolyan, and A. I. Subbotin, Zhur. Org. Khim., 6, 684 (1970).
62. I. V. Bodrikov, I. S. Okrokova, and V. R. Kartashov, Zhur. Org. Khim., 7, 1991 (1971).
63. Yu. V. Pokonova, "Galoidefiry" (Halogenated Ethers and Esters), Khimiya, Moscow–Leningrad, 1966, pp. 164, 208.
64. F. C. Weber, G. F. Hennion, and R. R. Vogt, J. Amer. Chem. Soc., 61, 1457 (1939).
65. A. I. Titov, F. L. Maklyaev, and V. G. Kuz'mina, Zhur. Obshch. Khim., 25, 744 (1955).
66. M. V. Likhosherstov and T. V. Shalaeva, Zhur. Obshch. Khim., 8, 370 (1938).
67. M. V. Likhosherstov, R. A. Arkhangel'skaya, and T. V. Shalaeva, Zhur. Obshch. Khim., 9, 2085 (1939).
68. C. F. Irwin and G. F. Hennion, J. Amer. Chem. Soc., 63, 858 (1941).
69. A. I. Titov and F. L. Maklyaev, Zhur. Obshch. Khim., 24, 1631 (1954).
70. A. I. Titov and F. L. Maklyaev, Zhur. Obshch. Khim., 24, 1960 (1954).
71. A. A. Petrov, Zhur. Obshch. Khim., 19, 1046 (1949).
72. A. A. Petrov, "Voprosy Khimicheskoi Kinetiki, Kataliza i Reaktsionnoi Sposobnosti" (Aspects of Chemical Kinetics, Catalysis, and Reactivity), Izd. Akad. Nauk SSSR, 1955, p. 765.
73. V. L. Heasley and P. H. Chamberlain, J. Org. Chem., 35, 539 (1970).
74. R. Riemschneider and R. Nehring, Annalen, 660, 41 (1962).
75. T. A. Zyryanova and A. A. Petrov, Zhur. Obshch. Khim., 26, 2189 (1956).
76. W. Oroshik and R. A. Mallory, J. Amer. Chem. Soc., 72, 4610 (1950).
77. A. A. Petrov, Zhur. Obshch. Khim., 10, 1682 (1940).
78. A. A. Petrov, Zhur. Obshch. Khim., 10, 819 (1940).
79. A. A. Petrov, Dokl. Akad. Nauk SSSR, 78, 62 (1951).
80. A. A. Petrov, Zhur. Obshch. Khim., 22, 1516 (1952).
81. A. A. Petrov and Yu. I. Porfir'eva, Dokl. Akad. Nauk SSSR, 90, 561 (1953).
82. A. A. Petrov, Uspekhi Khim., 29, 1050 (1960) [Russ. Chem. Rev., No. 9 (1960)].
83. K. Weisermel and M. Lederer, Chem. Ber., 96, 77 (1963).
84. S. Winstein and L. Goodman, J. Amer. Chem. Soc., 76, 4368 (1954).
85. L. S. Boguslavskaya, K. V. Yarovykh, and A. B. Bulovyatova, Zhur. Org. Khim., 5, 1932 (1969).
86. S. Winstein and L. Goodman, J. Amer. Chem. Soc., 76, 4373 (1954).
87. V. R. Kartashov, E. N. Krom, and I. V. Bodrikov, Zhur. Org. Khim., 6, 15 (1970).
88. V. R. Kartashov and I. V. Bodrikov, Zhur. Org. Khim., 2, 1119 (1966).
89. I. V. Bodrikov, V. R. Kartashov, and T. I. Temnikova, Zhur. Org. Khim., 3, 669 (1967).
90. V. R. Kartashov and I. V. Bodrikov, Zhur. Org. Khim., 4, 571 (1968).
91. V. R. Kartashov and I. V. Bodrikov, Zhur. Org. Khim., 3, 776 (1967).
92. I. V. Bodrikov, V. R. Kartashov, and T. I. Temnikova, Zhur. Org. Khim., 4, 1333 (1968).
93. V. R. Kartashov, V. P. Pushkarev, and I. V. Bodrikov, Zhur. Org. Khim., 6, 2147 (1970).
94. V. R. Kartashov, V. P. Pushkarev, and I. V. Bodrikov, Zhur. Org. Khim., 6, 2183 (1970).
95. V. R. Kartashov, V. P. Pushkarev, I. V. Bodrikov, and K. N. Tishkov, Zhur. Org. Khim., 7, 1570 (1971).
96. V. R. Kartashov, V. P. Pushkarev, and I. V. Bodrikov, Zhur. Org. Khim., 7, 1574 (1971).
97. V. R. Kartashov, V. P. Pushkarev, K. N. Tishkov, and I. V. Bodrikov, Zhur. Org. Khim., 7, 1578 (1971).
98. I. V. Knunyants, E. Ya. Pervova, and V. V. Tyuleneva, Izv. Akad. Nauk SSSR, Ser. Khim., 843 (1956).
99. R. Kh. Freidlina, V. N. Kost, and A. N. Nesmeyanov, Izv. Akad. Nauk SSSR, Ser. Khim., 1202 (1956).
100. A. N. Nesmeyanov, R. Kh. Freidlina, and A. B. Belyavskii, Izv. Akad. Nauk SSSR, Ser. Khim., 1028 (1959).
101. A. N. Nesmeyanov, R. Kh. Freidlina, V. N. Kost, T. T. Vasiljeva, and B. V. Kopilova, Tetrahedron, 17, 69 (1962).
102. L. S. Boguslavskaya and A. B. Bulovyatova, Zhur. Org. Khim., 7, 443 (1971).
103. L. S. Boguslavskaya and V. S. Etlis, Zhur. Org. Khim., 7, 1811 (1971).
104. L. B. Ziegler and A. C. Shabica, J. Amer. Chem. Soc., 74, 4891 (1952).
105. S. Mori, J. Chem. Soc. Japan, 64, 981 (1943).
106. C. H. Robinson, L. Finckenor, M. Kirtley, G. Gould, and E. Oliveto, J. Amer. Chem. Soc., 81, 2191 (1959).
107. C. H. Robinson, L. Finckenor, E. Oliveto, and G. Gould, J. Amer. Chem. Soc., 81, 4107 (1959).
108. A. Bowers, J. Amer. Chem. Soc., 81, 4107 (1959).
109. A. Bowers, L. C. Ibanez, E. Denot, and R. Becerra, J. Amer. Chem. Soc., 82, 4001 (1960).
110. A. Bowers, E. Denot, and R. Becerra, J. Amer. Chem. Soc., 82, 4007 (1960).
111. A. K. Bose, K. G. Das, and T. M. Jacob, Chem. and Ind., 452 (1963).
112. A. K. Bose, K. G. Das, and P. T. Funke, J. Org. Chem., 29, 1202 (1964).
113. I. L. Knunyants and L. S. German, Izv. Akad. Nauk SSSR, Ser. Khim., 1065 (1966).
114. F. L. M. Pattison, D. A. V. Peters, and F. H. Dean, Canad. J. Chem., 43, 1689 (1965).
115. F. H. Dean and F. L. M. Pattison, Canad. J. Chem., 43, 2465 (1965).
116. L. S. Boguslavskaya, K. V. Yarovykh, A. P. Sineokov, V. S. Etlis, and A. B. Bulovyatova, Zhur. Org. Khim., 8, 1139 (1972).
117. L. S. Boguslavskaya, V. S. Etlis, K. V. Yarovykh, and A. V. Bulovyatova, Zhur. Org. Khim., 7, 1338 (1971).
118. B. L. Dyatkin, E. P. Mochalina, and I. L. Knunyants, Uspekhi Khim., 35, 979 (1966) [Russ. Chem. Rev., No. 6 (1966)].
119. B. L. Dyatkin and I. L. Knunyants, Zhur. Vses. Khim. Obshch. Mendeleeva, 15, 5 (1970).
120. T. I. Limasova, A. G. Rumyantseva, M. I. Kollegova, S. G. Chernyakhovskaya, E. I. Berus, and V. A. Barkhash, Zhur. Org. Khim., 7, 750 (1971).
121. L. S. Boguslavskaya, V. S. Etlis, K. V. Yarovykh, and A. V. Bulovyatova, Zhur. Org. Khim., 8, 1147 (1972).
122. W. H. Puterbaugh and M. S. Newman, J. Amer. Chem. Soc., 79, 3469 (1957).
123. M. S. Newman (Editor), "Steric Effects in Organic Chemistry", (Translated into Russian), Inostr. Lit., Moscow, 1960, p. 251.

124. M. F. Shostakovskii, N. A. Keiko, and A. Kh. Filippova, Izv. Akad. Nauk SSSR, Ser. Khim., 392 (1967).
125. N. A. Keiko, A. P. Chichkarev, and M. F. Shostakovskii, Izv. Akad. Nauk SSSR, Ser. Khim., 660 (1971).
126. B. L. Dyatkin, Yu. A. Kotikyan, and I. L. Knunyants, Dokl. Akad. Nauk SSSR, 199, 1066 (1971).
127. E. A. Shilov, see Ref. 72, p. 749.
128. Yu. A. Serguchev and E. A. Shilov, Ukrain. Khim. Zhur., 32, 34 (1966).
129. E. A. Shilov, Zhur. Vses. Khim. Obshch. Mendeleeva, 7, 419 (1962).
130. Yu. A. Serguchev and E. A. Shilov, Dokl. Akad. Nauk SSSR, 155, 1383 (1964).
131. A. I. Titov and F. L. Maklyaev, Zhur. Obshch. Khim., 24, 1624 (1954).
132. T. I. Temnikova, "Kurs Teoreticheskikh Osnov Organicheskoi Khimii" (Course in the Theoretical Foundations of Organic Chemistry), Khimiya, Leningrad, 1968, p. 493.