

## Liquid Phase Halogenation with Metal Halides

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Recent studies on the liquid phase halogenation of alkanes, olefins, acetylenes, and arenes with metal or metalloidal halides are reviewed. Some characteristics in these halogenation, reactions, as compared with halogenation by molecular halogens, are mentioned.

Various kinds of halogenating agents have been employed to replace a hydrogen atom in paraffinic and aromatic hydrocarbons with a halogen atom, or to add a halogen molecule to unsaturated hydrocarbons, though certain choice of reagent depending on substrate would be necessary. Liquid phase halogenation of various hydrocarbons with metal or metalloidal halides, which are mostly used in the form of higher valency states, shows interesting features in many respects, particularly in selectivities. In this paper, several recent results on these halogenation reactions, including our data are reviewed concisely, placed an emphasis on comparisons between halogen and metal halide halogenation.

### I. HALOGENATION OF OLEFINS AND ACETYLENES

Several metal and metalloidal halides ( $\text{CuBr}_2$ ,  $\text{CuCl}_2$ ,  $\text{SbCl}_5$ ,  $\text{TiCl}_3 \cdot 4\text{H}_2\text{O}$ ,  $\text{PCl}_5$ ,  $\text{AuCl}_3$  etc.) have been known to effect direct halogenation of olefins or acetylenes. Various examples are collected in Table 1. Some data relating to product distribution and stereochemistry are also summarized in Table 2.























Halogenation with  $\text{CuX}_2$  ( $\text{X} = \text{Br}, \text{Cl}$ ) is easily achieved in a homogeneous system using acetonitrile (with<sup>1)</sup> or without<sup>2)</sup>  $\text{LiX}$  as solvent. Though other solvents such as alcohols<sup>1,3)</sup> and acetic acid (with  $\text{NaOAc}$ )<sup>1)</sup> can be used effectively for this reaction, the formation of solvent-incorporated products is unavoidable owing to their high nucleophilicity. The reactivity of olefins toward  $\text{CuX}_2$  suggests that this halogenation would be surely electrophilic. As for  $\text{CuBr}_2$ , the reaction is completely stereospecific and *trans*; whereas in the case of less reactive  $\text{CuCl}_2$ , the specificity is considerably sensitive to substrate structure and reaction medium.<sup>4)</sup> In contrast to this, the addition of bromine or chlorine to simple olefins is known to be highly stereospecific. A predominant *trans*-1,4-adduct formation from butadiene and  $\text{CuBr}_2$  would be interesting, since the fact is known that the halogenation with bromine molecule affords nearly equal amounts of 1,2- and *trans*-1,4-dibromides (as kinetically controlled products) in various solvents.<sup>5)</sup>

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

















Table 2. Product Distribution and Stereochemistry in Halogenation of Olefins

Substrate	Halogen source	Reaction Conditions	Product (Yield, %)	trans Addition	Ref.
$c\text{-CH}_3\text{-CH=CH-CH}_3$	Br <sub>2</sub>	in CH <sub>3</sub> CN, 25°	$dl\text{-CH}_3\text{CHBrCHBrCH}_3$	100	16
$c\text{-CH}_3\text{-CH=CH-CH}_3$	CuBr <sub>2</sub>	in CH <sub>3</sub> CN, 25°, 10 min	$dl\text{-CH}_3\text{CHBrCHBrCH}_3$ (91)	100	2
$t\text{-CH}_3\text{-CH=CH-CH}_3$	Cl <sub>2</sub>	in CF <sub>2</sub> ClCFCl <sub>2</sub> , -9°	$meso\text{-CH}_3\text{CHClCHClCH}_3$	100	17
$t\text{-CH}_3\text{-CH=CH-CH}_3$	CuCl <sub>2</sub>	in CH <sub>3</sub> OH, 140°, 3 hr	$meso\text{-}$ & $dl\text{-CH}_3\text{CHClCHClCH}_3$ (10)	62	4
$t\text{-CH}_3\text{-CH=CH-CH}_3$	SbCl <sub>5</sub>	in CCl <sub>4</sub> , 76°, 10 min	$meso\text{-}$ & $dl\text{-CH}_3\text{CHClCHClCH}_3$ (96)	18	8
	Br <sub>2</sub>	in CH <sub>3</sub> CN, 0°, 1.5 hr	 (63) &  (27)	100	2
	CuBr <sub>2</sub>	in CH <sub>3</sub> CN, 0°, 1.5 hr	 (93) &  (1)	100	2
	Cl <sub>2</sub>	in CCl <sub>4</sub> , 0°, 10 min		100	9
	CuCl <sub>2</sub>	in CH <sub>3</sub> CN, 60-80°, 2-4 hr	$c\text{-}$ & $t\text{-}$  (73)	95	2
	CuCl <sub>2</sub>	in AcOH, 150°, 2 hr	$c\text{-}$ & $t\text{-}$ 	88	4
	SbCl <sub>5</sub>	in CCl <sub>4</sub> , 76°, 5 min	$c\text{-}$ & $t\text{-}$  (67)	17	8
	TiCl <sub>3</sub> ·4H <sub>2</sub> O	in CCl <sub>4</sub> , 76°, 2 hr	$c\text{-}$ & $t\text{-}$  (17)	98	11
	PCl <sub>5</sub>	neat, 80°, 10 hr	 (87)	100	12
CH <sub>2</sub> =CH-CH=CH <sub>2</sub>	CuBr <sub>2</sub>	in CH <sub>3</sub> CN, 25°, 10 min	only $t\text{-BrCH}_2\text{CH=CHCH}_2\text{Br}$ (92)	—	2
CH <sub>2</sub> =CH-CH=CH <sub>2</sub>	CuCl <sub>2</sub>	in CH <sub>3</sub> CN, 60°, 2-4 hr	a mixture of CH <sub>2</sub> ClCHCl-CH=CH <sub>2</sub> , $c\text{-}$ & $t\text{-ClCH}_2\text{CH=CHCH}_2\text{Cl}$ (43) (ratio 15 : 5 : 80)	—	2
CH <sub>2</sub> =CH-CH=CH <sub>2</sub>	SbCl <sub>5</sub>	in CCl <sub>4</sub> , 0°, 10 min	a mixture of CH <sub>2</sub> ClCHCl-CH=CH <sub>2</sub> , $c\text{-}$ & $t\text{-ClCH}_2\text{CH=CHCH}_2\text{Cl}$ (50) (ratio 32 : 21 : 47)	—	9
	Cl <sub>2</sub>	in CH <sub>3</sub> CN, 6-11°	$c\text{-}$ & $t\text{-}$  (trace amounts)	95	18
	CuCl <sub>2</sub>	in CH <sub>3</sub> CN + LiCl, 82°, 22 hr	$c\text{-}$ & $t\text{-}$  (58)	70	18

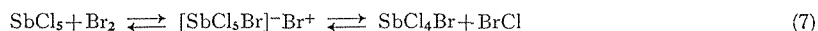


## Liquid Phase Halogenation with Metal Halides

Table 3. Mixed Halogenation of Olefins with Mixtures of Metal Halides and Halogen Donors

Olefin	Metal Halide & Halogen Donor (molar ratio)	Reaction Conditions	Product (Yield %)	Ref.
CH <sub>2</sub> =CH <sub>2</sub>	CuCl <sub>2</sub> +I <sub>2</sub> (2:1)	in C <sub>6</sub> H <sub>12</sub> , 80°, 2 hr	ICH <sub>2</sub> CH <sub>2</sub> Cl (85)	2
CH <sub>2</sub> =CH-OCOCH <sub>3</sub>	CuCl <sub>2</sub> +I <sub>2</sub> (2:1)	in CH <sub>3</sub> CN, 25°, 2 hr	CH <sub>2</sub> ICHCl(OCOCH <sub>3</sub> ) (83)	2
CH <sub>3</sub> CH=CH <sub>2</sub>	CuCl <sub>2</sub> +I <sub>2</sub> (2:1)	in CH <sub>3</sub> CN, 50°, 2 hr	CH <sub>3</sub> CHClCH <sub>2</sub> I (64) & CH <sub>3</sub> CHICH <sub>2</sub> Cl (21)	2
CH <sub>2</sub> =CH-Cl	CuCl <sub>2</sub> +I <sub>2</sub> (2:1)	in CH <sub>3</sub> CN, 50°, 15 hr	CH <sub>2</sub> ICHCl <sub>2</sub> (57) & CH <sub>2</sub> ClCHCl (24)	2
(CH <sub>3</sub> ) <sub>2</sub> C=CH <sub>2</sub>	HgCl <sub>2</sub> +I <sub>2</sub> (1:2)	in (C <sub>2</sub> H <sub>5</sub> ) <sub>2</sub> O, 25°, 1 hr	(CH <sub>3</sub> ) <sub>2</sub> CClCH <sub>2</sub> I (67)	13
C <sub>6</sub> H <sub>5</sub> CH=CH <sub>2</sub>	CuCl <sub>2</sub> +KI (2:1)	in CH <sub>3</sub> CN, 80°, 1 hr	C <sub>6</sub> H <sub>5</sub> CHClCH <sub>2</sub> I (75)	2
	CuCl <sub>2</sub> +I <sub>2</sub> (2:1)	in CH <sub>3</sub> CN, 80°, 2 hr	 (90)	2
	CuCl <sub>2</sub> +KI (2:1)	in CH <sub>3</sub> CN, 80°, 2 hr	 (78)	2
	SbCl <sub>5</sub> +I <sub>2</sub> (1:1)	in CCl <sub>4</sub> , 76°, 10 min	 (94)	14
	CuCl <sub>2</sub> +Br <sub>2</sub> (2:1)	in CH <sub>3</sub> CN, 80°, 1 hr	 (54) &  (23)	2
	CuCl <sub>2</sub> +NH <sub>4</sub> Br (2:1)	in CH <sub>3</sub> CN, 80°, 1 hr	 (47) &  (3)	2
	SbCl <sub>5</sub> +Br <sub>2</sub> (1:1)	in CCl <sub>4</sub> , 30°, 5 min	 (96) &  (~0)	14
	SbCl <sub>5</sub> +LiBr (1:1)	in CCl <sub>4</sub> , 76°, 5 min	 (81),  (~0) & <i>c-, t-</i>  (trace)	14
C <sub>6</sub> H <sub>5</sub> CH=CH <sub>2</sub>	SbCl <sub>5</sub> +Br <sub>2</sub> (1:1)	in CCl <sub>4</sub> , 0°, 10 min	C <sub>6</sub> H <sub>5</sub> CHClCH <sub>2</sub> Br (87)	14

*trans* fashion with high stereospecificity, and the products are generally in accord with Markovnikov's rule. No competitive iodination is found in chloriodination; whereas considerable competition with bromine is observed in chlorobromination, depending on the redox combination. This is largely due to differences in reactivities between halogens and mixed halogens (relative reactivities<sup>15</sup>); I<sub>2</sub> : ICl = 1 : 10<sup>5</sup>, Br<sub>2</sub> : BrCl = 1 : 4 × 10<sup>2</sup>. In addition, if the formation of a mixed halogen proceeds through an ionic adduct (*e.g.*, eq. 7), the Lewis acidity of an original metal halide would become an important factor



for the concentration of a mixed halogen. In fact, it has been found<sup>14</sup>) that the product selectivity in chlorobromination decreases as the Lewis acidity of metal chlorides decreases.

## II. HALOGENATION OF ARENES

For the halogenation of rather reactive aromatics, the use of various metal or metalloid halides ( $\text{SbCl}_5$ ,  $\text{FeCl}_3$ ,  $\text{VCl}_4$ ,  $\text{MoCl}_5$ ,  $\text{PCl}_5$ ,  $\text{TiCl}_3 \cdot 4\text{H}_2\text{O}$ ,  $\text{CuBr}_2$ ,  $\text{TlBr}_3 \cdot 4\text{H}_2\text{O}$  etc.) as halogenating agents has been reported. Representative examples are summarized in Table 4. Isomer distribution and relative rate data in the halogenation of toluene using various halogenating agents are collected in Table 5.

Based on the reactivity toward aromatics and the favorable *ortho-para* orientation, the halogenation with Lewis acid halides is considered to proceed by an electrophilic

Table 4. Aromatic Halogenation with Metal Halides

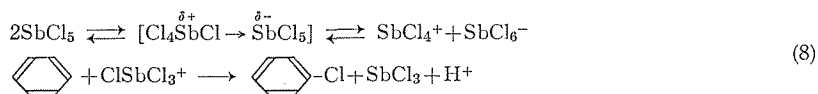
Aromatic compound	Halogenating agent	Reaction Conditions	Product (Yield, %; <i>o/p</i> ratio)	Ref.
$\text{C}_6\text{H}_5\text{Cl}$	$\text{SbCl}_5$	neat, 41–59°, 2 hr	$\text{C}_6\text{H}_4\text{Cl}_2$ (82 ; 0.2)	20
$\text{C}_6\text{H}_5\text{Cl}$	$\text{FeCl}_3$	neat, 125–140°, 3 hr	$\text{C}_6\text{H}_4\text{Cl}_2$ (86 ; 0.1)	19
$\text{C}_6\text{H}_5\text{Cl}$	$\text{VCl}_4$	neat, 118–121°, 2.5 hr	$\text{C}_6\text{H}_4\text{Cl}_2$ (70 ; 0.2)	21
$\text{C}_6\text{H}_5\text{Cl}$	$\text{MoCl}_5$	neat, 105–110°, 2.5 hr	$\text{C}_6\text{H}_4\text{Cl}_2$ (31 ; 0.1)	21
$\text{C}_6\text{H}_5\text{CH}_3$	$\text{SbCl}_5$	neat, 18–31°, 2.5 hr	$\text{CH}_3\text{C}_6\text{H}_4\text{Cl}$ (87 ; 0.9)	20
$\text{C}_6\text{H}_5\text{CH}_3$	$\text{TlBr}_3 \cdot 4\text{H}_2\text{O}$	in $\text{CCl}_4$ , 78°, 1 hr	$\text{CH}_3\text{C}_6\text{H}_4\text{Br}$ (20 ; 1.6)	24
$\text{C}_6\text{H}_5\text{CH}_3$	$\text{TiCl}_3 \cdot 4\text{H}_2\text{O}$	in $\text{CCl}_4$ , 78°, 2 hr	$\text{CH}_3\text{C}_6\text{H}_4\text{Cl}$ (28 ; 1.0) & $\text{CH}_3\text{C}_6\text{H}_4\text{COOH}$ (10;0.7)	22
Anthracene	$\text{CuCl}_2$	in $\text{CCl}_4$ , 78°, 7 hr	9-Chloroanthracene (98)	27
$\text{C}_6\text{H}_5\text{OH}$	$\text{CuCl}_2$	in DMF+LiCl, 150°, 5 min	$\text{ClC}_6\text{H}_4\text{OH}$ (60 ; 0.1–0.2)	25
$\beta\text{-C}_{10}\text{H}_7\text{OH}$	$\text{CuBr}_2$	in aq. $\text{CH}_3\text{OH}$ +KBr, 25°, 15 hr	$\alpha\text{-Bromo-}\beta\text{-naphthol}$ (50)	26
$\text{C}_6\text{H}_6$	$\text{AlI}_3$ + $\text{CuCl}_2$	neat, 80°, 5 hr	$\text{C}_6\text{H}_5\text{I}$ (65)	28
$\text{C}_6\text{H}_5\text{CH}_3$	$\text{FeI}_2 \cdot 4\text{H}_2\text{O}$ + $\text{CuCl}_2$	neat, 110°, 3 hr	$\text{CH}_3\text{C}_6\text{H}_4\text{I}$ (81 ; 1.1)	28
$\text{C}_6\text{H}_5\text{OH}$	$\text{I}_2$ + $\text{CuCl}_2$	in $\text{C}_6\text{H}_5\text{Cl}$ , 130°, 29 hr	$p\text{-IC}_6\text{H}_4\text{OH}$ (69)	28
$\text{C}_6\text{H}_5\text{N}(\text{CH}_3)_2$	$\text{I}_2$ + $\text{CuCl}_2$	in $\text{C}_6\text{H}_6$ , 60°, 0.5 hr	$p\text{-IC}_6\text{H}_4\text{N}(\text{CH}_3)_2$ (47)	28

Table 5. Isomer Distribution and Relative Rate in Halogenation of Toluene

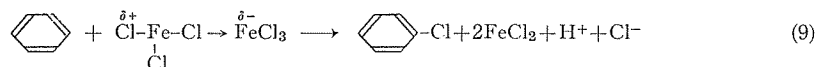
Halogen source	Reaction Conditions	Halotoluene			Rel. Rate $k_T/k_B$	Ref.
		Isomer Ratio				
		<i>o</i>	<i>m</i>	<i>p</i>		
$\text{Cl}_2$	in aq. $\text{CH}_3\text{COOH}$ , 25°	60	0.5	39.5	345	29
$\text{Cl}_2(\text{SbCl}_5 \text{ cat})$	neat, 25–30°	72	2	26	—	20
$\text{SbCl}_5$	neat, 18–31°	47	2	51	—	20
$\text{Cl}_2(\text{TiCl}_3 \cdot 4\text{H}_2\text{O} \text{ cat})$	in $\text{CCl}_4$ , 78°	64	0	36	43	23
$\text{TiCl}_3 \cdot 4\text{H}_2\text{O}$	in $\text{CCl}_4$ , 78°	52	0	48	26	23
$\text{FeCl}_3$	neat, 50–60°	12	<1	88	—	19
$\text{VCl}_4$	neat, 7–25°	15	1	84	—	21
$\text{Br}_2$	in aq. $\text{CH}_3\text{COOH}$ , 25°	33	0	67	605	29
$\text{Br}_2(\text{TlBr}_3 \cdot 4\text{H}_2\text{O} \text{ cat})$	in $\text{CCl}_4$ , 78°	58	0	42	7	24
$\text{TlBr}_3 \cdot 4\text{H}_2\text{O}$	in $\text{CCl}_4$ , 78°	62	0	38	15	24

substitution. The rough chlorinating ability is given in the following order;  $\text{SbCl}_5 > \text{FeCl}_3$ ,  $\text{VCl}_4 > \text{MoCl}_5$ ,  $\text{CuCl}_2$ , and this correlates well with their oxidizing ability.<sup>19-21)</sup> Though the activity of  $\text{TiCl}_3 \cdot 4\text{H}_2\text{O}$  appears to be rather low, the reaction with this chloride in carbon tetrachloride shows somewhat different behavior, *i.e.*, conversion of benzene into chlorobenzene and benzoic acid occurs concurrently.<sup>22)</sup>

Isomer distributions in metal chloride chlorination of toluene are clearly different from those in chlorination using chlorine molecule without or with metal chloride catalysts. This implies that metal chloride can effect substitution without prior degradation to free chlorine and the electrophiles here would be species other than  $\text{Cl}_2$  and  $\text{Cl}^+$ . When  $\text{SbCl}_5$  or  $\text{TiCl}_3 \cdot 4\text{H}_2\text{O}$  is the reagent, somewhat lower *o/p* ratios and considerably low  $k_T/k_B$  value are obtained, and this suggests that a reactive and somewhat bulky attacking species, such as  $\text{SbCl}_4^+$  and  $\text{TiCl}_2^+$ , may function (see eq. 8).<sup>20,23)</sup> In cases of  $\text{FeCl}_3$ ,  $\text{VCl}_4$ ,



and  $\text{MoCl}_5$ , the attack of a polarized dimer complex, which is more bulky, has been postulated on the basis of quite less *ortho*-substitution (see eq. 9).<sup>19,21)</sup>



On the other hand, the selectivity data in the bromination with  $\text{TlBr}_3 \cdot 4\text{H}_2\text{O}$  indicate that the reaction is essentially the same as that with bromine in the presence of  $\text{TlBr}_3$  catalyst.<sup>24)</sup>

Though  $\text{CuX}_2$  can also act as aromatic halogenating agents, this halogenation seems to be applicable to highly reactive aromatic components, such as phenols,<sup>25,26)</sup> aromatic amines,<sup>26)</sup> and polynuclear hydrocarbons.<sup>27)</sup> An interesting use of this halogenation would be the preparation of *p*-halogenated compounds of phenols and anilines. In this reaction *para*-substitution predominates, whereas usual halogenation affords a mixture of *o*- and *p*-halogenated, and/or polyhalogenated compounds.



Aromatic iodination with  $\text{CuCl}_2$ -iodine donor combinations (*cf.* eq. 5 and 6) has recently been developed.<sup>28)</sup> Some examples are included in Table 4.  $\text{FeI}_2$  and  $\text{AlI}_3$  exhibit higher reactivity than iodine itself. The reaction would be essentially electrophilic, and is not applicable to strongly deactivated aromatics (*e.g.*, benzoic ester). Aromatics possessing functional groups that coordinate with copper salt (*e.g.*, aniline, thiophene) are often not iodinated.

### III. HALOGENATION OF ALKANES

The halogenation of aliphatic hydrocarbons with chlorine or bromine molecule is usually performed in the presence of light. A few metal or metalloidal halides (*e.g.*,  $\text{PCl}_5$ ,  $\text{SbCl}_5$ ,  $\text{FeCl}_3$  *etc.*) can be used in place of halogen elements. Some examples are given in Table 6.

$\text{PCl}_5$  can react smoothly with alkanes in an inert solvents such as *o*-dichlorobenzene

Table 6. Halogenation of Some Aliphatic Compounds with Metal and Metalloidal Halides

Substrate	Halide	Reaction Conditions	Product (Yield, %)	Ref.
<i>n</i> -C <sub>7</sub> H <sub>16</sub>	PCl <sub>5</sub>	in <i>o</i> -C <sub>6</sub> H <sub>4</sub> Cl <sub>2</sub> , BPO cat, 90°, 8 hr	Mixed chloroheptanes (73)	12
	PCl <sub>5</sub>	in <i>o</i> -C <sub>6</sub> H <sub>4</sub> Cl <sub>2</sub> , BPO cat, 88°, 7 hr	 -Cl (70)	12
Adamantane	SbCl <sub>5</sub>	in CH <sub>2</sub> Cl <sub>2</sub> , 40°, 3 hr	1- & 2-Chloroadamantane (69)	31
C <sub>6</sub> H <sub>5</sub> CH <sub>2</sub> CH <sub>3</sub>	PCl <sub>5</sub>	neat, 105°, 16 hr	C <sub>6</sub> H <sub>5</sub> CHClCH <sub>3</sub> (60)	12
(C <sub>6</sub> H <sub>5</sub> ) <sub>3</sub> CH	PCl <sub>5</sub>	neat, 140-150°, 18 hr	(C <sub>6</sub> H <sub>5</sub> ) <sub>3</sub> CCl (93)	35
CH <sub>3</sub> CH <sub>2</sub> CH <sub>2</sub> CHO	CuBr <sub>2</sub>	in CH <sub>3</sub> OH, 64°, 9 hr	CH <sub>3</sub> CH <sub>2</sub> CHBrCH(OCH <sub>3</sub> ) <sub>2</sub> (40)	3
CH <sub>3</sub> CH <sub>2</sub> CH <sub>2</sub> CHO	CuCl <sub>2</sub>	in DMF, 85°, 2 hr	CH <sub>3</sub> CH <sub>2</sub> CHClCHO (60)	3
CH <sub>3</sub> COC <sub>2</sub> H <sub>5</sub>	CuCl <sub>2</sub>	in DMF+LiCl, 80-90°, 0.75 hr	CH <sub>3</sub> COCHClCH <sub>3</sub> ( <i>ca.</i> 60)	25
C <sub>6</sub> H <sub>5</sub> COC <sub>2</sub> H <sub>5</sub>	CuCl <sub>2</sub>	in DMF+LiCl, 80-90°, 1 hr	C <sub>6</sub> H <sub>5</sub> COCHClCH <sub>3</sub> (72)	25

to yield alkyl chlorides, in the absence or presence of an initiator (*e.g.*, benzoyl peroxide).<sup>12)</sup> Owing to a radical nature of the reaction, the product generally consists of a mixture of isomeric chlorides except for some cases such as the chlorination of unsubstituted cycloalkanes and monoalkylated aromatics. Interestingly, the reaction with olefins affords only dichlorides (*cf.* section I), and does not cause any attack on allyl position in olefins even in the presence of peroxide. Through competitive experiments between toluene and cyclohexane, it has been found that the thermal PCl<sub>5</sub> reaction has almost the same selectivity as photochlorination (relative reactivities: toluene/cyclohexane (both per C-H), PCl<sub>5</sub> reaction 3.0, photoreaction 2.8). Thus the attacking entity is probably a chlorine atom formed through eq. 10<sup>12)</sup> On the other hand, in the peroxide-catalyzed

Table 7. Isomer Distribution in Chlorination of *n*-Heptane and Adamantane(a) Chlorination of *n*-Heptane (Ref. 30)

Halogene source	Reaction Conditions	<i>n</i> -Chloro- <i>n</i> -heptane			
		1-	2-	3-	4-
Cl <sub>2</sub>	BPO cat., 98°	15.1	34.6	33.8	16.5
PCl <sub>5</sub>	BPO cat., 98°	2.5	36.4	41.5	19.5
PCl <sub>3</sub> +Cl <sub>2</sub>	BPO cat., 98°	traces	24.0	52.0	24.0

## (b) Chlorination of Adamantane (Ref. 31)

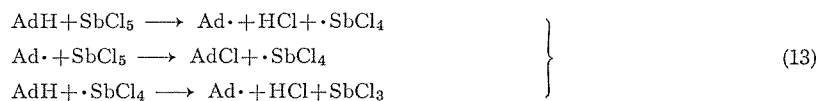
Halogene source	Reaction Conditions	Chloroadamantane 1/2 ratio
Cl <sub>2</sub>	in SnCl <sub>4</sub> ( $\epsilon=2.87$ ), 100°, 5 min	0.6
Cl <sub>2</sub>	in CH <sub>2</sub> Cl <sub>2</sub> ( $\epsilon=9.08$ ), 40°, 3 hr	0.5
FeCl <sub>3</sub>	in SnCl <sub>4</sub> , 110°, 3 hr	9-10
FeCl <sub>3</sub>	in CH <sub>2</sub> Cl <sub>2</sub> , 40°, 7 hr	20
SbCl <sub>5</sub>	in SnCl <sub>4</sub> , 110°, 15 min	9-10
SbCl <sub>5</sub>	in CCl <sub>2</sub> FCClF <sub>2</sub> ( $\epsilon=2.24$ ), AlCl <sub>3</sub> added, 40°, 20-30 min	>90



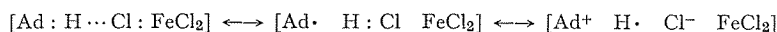
chlorination of *n*-heptane with  $\text{PCl}_5$  and with  $\text{Cl}_2$ , somewhat different isomer distributions have been observed (see Table 7).<sup>30)</sup> A suggested scheme<sup>12)</sup> involving the attack of  $\cdot\text{PCl}_4$  (partly  $\cdot\text{Cl}$ ) (eq. 11) would be reasonable.



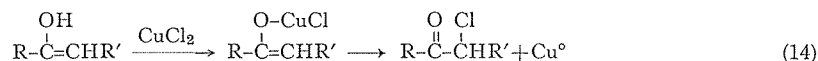
A similar reaction of  $\text{FeCl}_3$  or  $\text{SbCl}_5$  with C-H linkages has also been known.<sup>31)</sup> A radical nature of the reaction has been revealed by comparison of isomer distributions in chlorination of adamantane using various reagents such as  $\text{Cl}_2$ ,  $\text{FeCl}_3$ ,  $\text{SbCl}_5$ , and  $\text{SbCl}_5 + \text{AlCl}_3$  (see Table 7).  $\text{SbCl}_5$  reacts generally at a more rapid rate than  $\text{FeCl}_3$ . Further, photolytic conditions enhance the rate of the  $\text{SbCl}_5$  process, but does not promote the reaction with  $\text{FeCl}_3$ . This implies that  $\text{SbCl}_5$  may be involved in a radical chain process, whereas the  $\text{FeCl}_3$  reaction is probably a nonchain process. Based on these results the following radical pathway has been proposed for each chlorination.<sup>31)</sup>



Since a slight favorable effect on the rate is observed in a more polar solvent, the contribution of somewhat polar forms in the transition state may be considered. A similar situation has been known for hydrogen abstraction reactions involving chlorine atom.



In the halogenation of enolizable aldehydes or ketones, the use of  $\text{CuX}_2$  instead of halogen elements has been reported.<sup>25)</sup> The reaction proceeds smoothly in dimethylformamide solution. Some examples are included in Table 6. This reaction is essentially the same as the halogenation of phenols with  $\text{CuX}_2$  (*cf.* section II). As a probable pathway, the following scheme involving two-electron reduction of  $\text{Cu(II)}$  within a metal chloride-enolate complex has been suggested.<sup>25)</sup> The observed rates of the chlorination of



acetone in water<sup>32)</sup> and methanol,<sup>33)</sup> which are approximately expressed as a sum of second- and third-order terms, seem to agree with this mechanism. Here, the contribution of the third-order term appears to imply that an external attack of  $\text{Cl}^-$  (or  $\text{CuCl}_2$ ) on the complex may occur concurrently. A similar halogenation with  $\text{FeCl}_3$  in acetic acid has also been reported.<sup>34)</sup>

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