Selectivity in the Halogenation of Hexane by Tertiary Aminium Radicals from the Photodecomposition of *N*-Halogenoammonium Perchlorates[1]

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The photochlorination of hexane with tertiary *N*-chloroammonium perchlorates in trifluoroacetic acid gives monochlorohexanes in high yield and with a striking preference for the 2-isomer. It is shown that free-radical chains are involved in which hydrogen-atom abstraction is by tertiary aminium radicals. The marked preference for 2- compared with 3-chlorination is attributed mainly to the bulky aminium radical attacking the relatively more accessible 2-position; an alternative explanation involving a reversible hydrogen-atom abstraction is ruled out. The magnitude of the primary deuterium kinetic isotope effect in these photochlorinations gives information about the dependence of the extent of C–H bond breakage in the transition state on the structure of the abstracting aminium radical.

MIMICKING the regioselective functionalisation of saturated hydrocarbons that is achieved by micro-organisms under mild conditions[2] remains an attractive and challenging goal. In particular, reagents that would selectively oxidise the terminal methyl of a long-chain linear alkane could provide useful chemical intermediates.[3]

Although the functionalisation of alkanes by hydrogen-atom abstraction is not generally a very selective process,[4] aminium radicals show an unusually high degree of selectivity in their reactions with alkanes and substituted alkanes.[5] The potential of these species as selective hydrogen-atom abstractors has been investigated by Minisci [6] and Deno [7] and their co-workers, and it is clear from their results that the reactions of aminium radicals are very sensitive to both polar and steric effects. Thus the marked preference for ω-1 attack in the free-radical chlorinations, by secondary aminium radicals from *N*-chloroamines, of linear alkanes which have electron-attracting substituents at the 1-position, illustrates the polar preference of these electrophilic radical cations for the hydrogens in the methylene group furthest from the substituent.[6,7b] The similar, although less pronounced, selectivity for the ω-1 position of linear alkanes themselves has been attributed to steric hindrance;[6b,7d] that is, of all the methylene hydrogens in a linear alkane, those on the ω-1 positions are the most accessible to the bulky aminium radical.

The ready availability and purification of secondary *N*-halogenoamines[8] as a source for aminium radicals, compared with the analogous derivatives of primary and tertiary amines, has resulted in the almost exclusive use of secondary aminium radicals for studies in this area. However, we argued that the use of tertiary rather than secondary aminium radicals would increase the scope of structural and steric modifications in nitrogen radicals, and this might in turn lead to greater selectivity in hydrogen abstraction. In this paper we describe some of our studies on the free-radical halogenation of alkanes by tertiary aminium radicals derived from tertiary halogenoammonium ions, and we examine the origin of the selectivity of the reactions of these radical cations.

RESULTS AND DISCUSSION

Precursors for the Generation of Tertiary Aminium Radicals.—Preliminary experiments in which iron(II) was used to reduce tertiary amine *N*-oxides in acid solution[9] quickly revealed that this would not be a suitable source of tertiary aminium radicals for this study. *N*-Oxides are relatively easy to prepare from unhindered tertiary amines,[9a] but as the nitrogen becomes more encumbered so the preparation becomes more difficult. Further, the yield of products from hexane with this redox system was low (<10%). We attribute this to the ready competitive reduction of the aminium radicals by iron(II) and to the fact that, unlike the redox-initiated halogenations with secondary *N*-chloroammonium ions, the oxidations with *N*-oxides are not chain reactions.

The production of tertiary aminium radicals by the photolysis of tertiary chloroammonium ions largely overcame these problems. The method, a modification of the procedures of Böhme and Krause[10] and Danen and Rickard,[11] was typically to mix cooled solutions in tetrachloromethane of the tertiary amine and chlorine; the precipitated *N*-chloroammonium chloride was dissolved, without purification, in trifluoroacetic acid (TFA) and converted into the perchlorate salt by the addition of silver perchlorate [reaction (1)]. The majority of the unused chlorine was removed by purging the solution with nitrogen gas. The extent of the conversion of the tertiary amine into the *N*-chloroammonium salt was readily measured by ^{1}H n.m.r. spectroscopy of the TFA solution; the chemical shifts of the α-protons of the protonated amine are up-field from those of the *N*-chloroammonium ion and are split into a doublet by the NH proton.

$$R_3N + Cl_2 \longrightarrow R_3\overset{+}{N}Cl\ Cl^- \xrightarrow{AgClO_4} R_3\overset{+}{N}Cl\ ClO_4^- \quad (1)$$

Although tertiary *N*-bromoammonium salts can be prepared by the reaction of bromine with a tertiary amine

in tetrachloromethane,[10] they readily revert to bromine and the protonated amine when dissolved in TFA [reaction (2)]. The only solution of a tertiary *N*-bromoammonium perchlorate that we were able to prepare, using a modification of the general procedure, was that from 1-azabicyclo[2.2.2]octane.

$$R_3\overset{+}{N}Br + Br^- \xrightarrow{H^+} R_3\overset{+}{N}H + Br_2 \qquad (2)$$

For comparative studies a selection of secondary *N*-chloroamines and *N*-bromoamines was prepared.

Photolysis Conditions and Initiation of Chlorination of Hexane.—Some preliminary photochlorinations of hexane were with *N*-chloroammonium chlorides as the chlorinating agents, but these salts gave unreproducible yields and variable product distributions. It was especially notable that the latter invariably corresponded to a reagent of lower selectivity than that from the perchlorate salts, implying that, under the acid conditions, the chloroammonium chlorides partially revert to protonated amines and chlorine [reaction (3)], so that the products arise from chlorination by a mixture of free chlorine and *N*-chloroammonium salt. For this reason, the chlorinations with tertiary chloroammonium salts described in this study were with perchlorate as the counterion.

$$R_3\overset{+}{N}Cl + Cl^- \overset{H^+}{\rightleftharpoons} R_3\overset{+}{N}H + Cl_2 \qquad (3)$$

The chlorination of hexane with triethylchloroammonium perchlorate at 5 °C was examined under a variety of conditions (Table 1). The extent of reaction and the product distributions were monitored (g.l.c.) during the course of the reaction and after work-up on completion of reaction. Photolysis with the 1 kW u.v. lamp and a quartz reaction vessel was complete in 2 h and gave a product distribution that was dependent on the extent of reaction, whereas all the other photolyses required 6—8 h and gave monochlorohexane isomer distributions that were constant throughout the reaction. The conversion of *N*-chloroammonium salt into monochlorohexanes in all the photoinitiated reactions was >80%, but the redox-initiated chlorination [iron(II) sulphate] following the method of Minisci *et al.*[6] gave only a 50% yield of the monochlorohexanes. It is noteworthy that the product distributions obtained from all these chlorinations, except that from the 1 kW source, are the same within experimental error.

TABLE 1

Product distribution from the chlorination of hexane by *N*-chlorotriethylammonium perchlorate in TFA under nitrogen at 5 °C

Initiation method	Reaction vessel	Chlorohexane isomer distribution (%) 1	2	3
300 W quartz halogen lamp	Glass	4.4	75.8	19.8
300 W quartz halogen lamp	Quartz	4.4	76.0	19.6
100 W high pressure mercury u.v. lamp	Glass	3.0	77.6	19.4
1 kW xenon arc u.v. lamp	Glass	5.8	74.2	20.0
1 kW xenon arc u.v. lamp	Quartz	3.4	61.6	34.8
Fe^{II}–Fe^{III} redox		3.5	78.0	18.5

The yields of chlorohexanes from the thermal decomposition of *N*-chloroammonium salts in TFA containing hexane were much lower than those from the photoinitiated process (Table 2). To obtain appreciable yields of products, longer reaction times and higher temperatures were needed. Further, the thermal chlorinations were much less selective and the product distributions resembled those from photochlorination with free chlorine.

TABLE 2

Chlorination of hexane by the thermal decomposition of *N*-chloroammonium salts or the photolysis of chlorine in TFA under nitrogen

Chlorinating agent	Temp. (°C)	Reaction time (h)	Yield (%)	Chlorohexane isomer distribution (%) 1	2	3
$Me_3\overset{+}{N}Cl\ Cl^-$	4	60	5	26.5	37.0	36.5
$Me_3\overset{+}{N}Cl\ ClO_4^-$	20	40	5	23.9	40.0	36.1
$Et_3\overset{+}{N}Cl\ ClO_4^-$	20	100	25	23.7	39.2	37.1
Cl_2–$h\nu$	5	2		29.6	36.4	34.1

The most convenient procedure was that with a Pyrex reaction vessel and a 300 W quartz halogen lamp, and this was used for the photohalogenations discussed in the sequel. Typically, a solution of the *N*-halogenoammonium perchlorate in TFA was photolysed in the presence of excess of the alkane under nitrogen. With these conditions there was a high conversion of *N*-halogenoammonium salt into monohalogenoalkane, with dihalogenation accounting for <5% of the product.

It is unlikely that initiation of the photochlorinations is by the direct photolysis of the *N*-chloroammonium salt, since the Pyrex reaction vessel is essentially opaque to light of wavelength <300 nm, the quartz halogen lamp emits very little light below 350 nm, and the *N*-chloroammonium salts do not absorb appreciably above 325 nm.[12] It is probable that the aminium radicals are generated by chlorine-atom abstraction from the *N*-chloroammonium ion by radicals derived from an initiation process such as the photolysis of traces of chlorine in the reaction mixture [reaction (4)]. In

$$Cl_2 \longrightarrow 2Cl\cdot \xrightarrow[-HCl]{C_6H_{14}} C_6H_{13}\cdot \xrightarrow{R_3\overset{+}{N}Cl} R_3N^{+\cdot} + C_6H_{13}Cl \qquad (4)$$

accord with this, either when no attempt was made to remove the excess of chlorine from the reaction mixture or when an initiator (azobisisobutyronitrile) was added, the photolyses were quicker and, in the presence of large amounts of initiator or halogen, the product distribution became less selective, particularly in the early stages of the reaction.

It is probable that photolysis with the high-powered u.v. lamp with a quartz reaction vessel gives relatively high concentrations of aminium radicals and chlorine atoms by direct photolysis of the *N*-chloroammonium salt. The consequent chlorination by chlorine atoms would account for the less selective product distribution with this system.

We also observed that photochlorinations of hexane with the quartz halogen lamp and with highly purified *N*-chloropiperidine in TFA, in the absence of added initiator, proceeded very slowly and ceased before the *N*-chloroamine had all been consumed. When a photoinitiator was added to a reaction that had stopped, chlorination began again and continued until all the *N*-chloroamine had reacted.

Product Distributions from the Photohalogenation of Hexane and 2-Methylbutane with N-Halogenoammonium Salts.—The monohalogenohexane product distribution and the relative yields of 2- and 3-halogenohexane from photohalogenations of hexane with a range of *N*-halogenoammonium salts are recorded in Tables 3—6. The results from a limited study of the chlorination of 2-methylbutane are also included (Table 7). These photohalogenations are moderately selective and, for hexane, increasing the bulk of the alkyl groups attached to the nitrogen increases the yield of 1-halogenohexane and the selectivity for 2- rather than 3-halogenation.

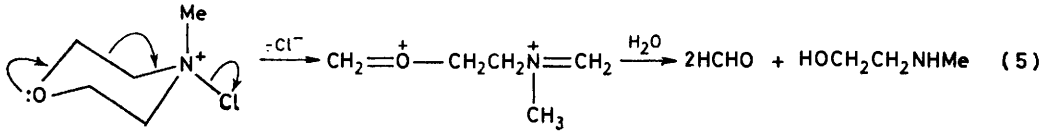


TABLE 3

Photochlorination of hexane by secondary *N*-chloroamines in TFA under nitrogen at 5 °C

N-Chloro-derivative of	Yield (%)	Chlorohexane isomer distribution (%) 1	2	3	Ratio of yields of 2- and 3-isomers
Piperidine	90	1.5	65.3	33.2	2.0
Dimethylamine	70	1.4	66.2	32.4	2.0
Dicyclohexylamine	30	6.7	65.9	27.3	2.4
Di-isopropylamine	30	6.8	65.9	27.3	2.4
2,2,6,6-Tetramethylpiperidine	85	6.4	75.4	18.2	4.1

TABLE 4

Photochlorination of hexane by cyclic tertiary *N*-chloroammonium perchlorates in TFA under nitrogen at 5 °C

N-Chloro-derivative of	Chlorohexane isomer distribution (%) 1	2	3	Ratio of yields of 2- and 3-isomers
1-Azabicyclo[2.2.2]octane	1.1	66.2	32.7	2.0
N-Methylmorpholine	2.9	70.6	26.5	2.7
N-Methylpiperidine	2.4	73.1	24.5	3.0
N-Methyl-9-azabicyclo-[3.3.1]nonane	3.0	74.0	23.0	3.2
cis-2,6-Dimethyl-*N*-methylpiperidine	4.3	75.1	20.6	3.6

TABLE 5

Photochlorination of hexane by acyclic tertiary *N*-chloroammonium perchlorates in TFA under nitrogen at 5 °C

N-Chloro-derivative of	Chlorohexane isomer distribution (%) 1	2	3	Ratio of yields of 2- and 3-isomers
Trimethylamine	3.9	68.2	27.8	2.5
Triethylamine	4.4	75.8	19.8	3.8
Dimethyl-t-butylamine	4.3	78.4	17.3	4.5
Di-isopropylmethylamine	7.1	76.6	16.5	4.7

TABLE 6

Photobromination of hexane in TFA under nitrogen at 5 °C

Brominating agent	Yield (%)	Bromohexane isomer distribution (%) 1	2	3	Ratio of yields of 2- and 3-isomers
Bromine		Trace	59.3	40.7	1.5
N-Bromodimethylamine	70	1.1	64.8	34.1	1.9
N-Bromo-2,2,6,6-tetramethylpiperidine	80	6.6	75.4	18.1	4.2
N-Bromo-1-azoniabicyclo-[2.2.2]octane perchlorate	30	0.8	63.4	35.8	1.8

TABLE 7

Photochlorination of 2-methylbutane in TFA under nitrogen at 5 °C

Chlorinating agent	Chloro-2-methylbutane isomer distribution (%) 1	2	3	4
Chlorine	36.8	15.4	30.3	17.6
N-Chloropiperidine	0.8	81.2	17.6	0.4
N-Chloro-2,2,6,6-tetramethylpiperidine	13.8	4.2	54.6	27.4

N-Chloro-*N*-methylmorpholinium perchlorate proved to be unstable in TFA, but a more stable solution was obtained when 5% fluorosulphonic acid was added. Presumably under the less acidic conditions the *N*-chloroammonium salt undergoes a Grob fragmentation similar to those reported by Rosenblatt and his coworkers [13] [reaction (5)]. Probably in the more acidic solution the salt is rendered less prone to this reaction by extensive protonation of the oxygen atom. However, even with the more acidic conditions, the yield of products from *N*-chloro-*N*-methylmorpholinium perchlorate was only 20%.

The Origin of the Selectivity of Hydrogen-atom Abstraction and the Nature of the Abstracting Species.—From Tables 3—6 it is clear that the distribution of halogenohexanes from photohalogenations with tertiary *N*-halogenoammonium salts is related to the structure of the alkyl group in these salts, is independent of the halogen, and is different from those obtained with the free halogen. These observations, combined with the known generation of tertiary aminium radicals from the photolysis of *N*-chloroammonium salts,[11,14] point to the hydrogen-abstracting agent being an aminium radical.

This conclusion is in keeping with the generally accepted view that, for halogenations with secondary *N*-halogenoamines in acid, the attacking species is a secondary aminium radical and not a halogen atom.[15]

An alternative explanation for the selectivity of the halogenation observed in this study comes from the work of Tanner and others [16] who have shown that, when hydrogen-atom abstraction from alkanes is reversible, the product distribution can become more selective. Thus the chlorovinylation of hexane, involving the reversible hydrogen-atom abstraction by chlorine atoms, gives 1-, 2-, and 3-substituted hexanes in the proportions 2.3, 77.1, and 20.6%, respectively,[16b] corresponding to a greater selectivity than is shown by chlorine atoms in irreversible hydrogen-atom abstractions (and, coincidentally, a similar distribution to that obtained with *N*-halogenoammonium ions).

$$R_3N^{+\bullet} + CH_3(CH_2)_4CH_3 \begin{cases} \xrightarrow{k_1^1} CH_3(CH_2)_4\dot{C}H_2 \xrightarrow[R_3N^+Cl]{k_2^1} CH_3(CH_2)_4CH_2Cl + R_3N^{+\bullet} \\ \xrightarrow{k_1^2} CH_3(CH_2)_3\dot{C}HCH_3 \xrightarrow{k_2^2} CH_3(CH_2)_3CHClCH_3 + R_3N^{+\bullet} \\ \xrightarrow{k_1^3} CH_3(CH_2)_2\dot{C}HCH_2CH_3 \xrightarrow{k_2^3} CH_3(CH_2)_2CHClCH_2CH_3 + R_3N^{+\bullet} \end{cases}$$

If the first of the propagating steps in the alkane chlorination is reversible, then the product distribution will depend not only on the k_1 values but also on the relative rates of the reverse reaction ($k_{-1}[C_6H_{13}\cdot][R_3\overset{+}{N}H]$) and the second propagating step ($k_2[C_6H_{13}\cdot][R_3\overset{+}{N}Cl]$). At the beginning of the reaction when $[R_3\overset{+}{N}H]$ is small and $[R_3\overset{+}{N}Cl]$ is large, the process would tend towards irreversibility and the product distribution would most nearly approximate to the actual selectivity of the abstracting radical. As the reaction proceeds $[R_3\overset{+}{N}H]$ should increase and $[R_3\overset{+}{N}Cl]$ decrease and the reverse of step 1 should become more significant. Under these circumstances the product distribution would change as the reaction progresses. This type of variation of the product distribution with yield has been observed in other chain reactions and has been used as evidence for the existence of a reversible step in the mechanism.[16] The absence of a variation in the product distribution with the extent of reaction in this study can only be accommodated by assuming that the reversible step takes place in a solvent cage where the two reactants do not diffuse apart and the effective $[R_3\overset{+}{N}H]$ is high even at the start of the reaction. However, we can rule out both simple reversibility and reversibility within a solvent cage for the following reasons.

(1) If reversible hydrogen-atom abstraction is taking place, then the product distribution should be sensitive to changes in k_2/k_{-1}. However, in the halogenation of hexane, changing the halogenating agent from an *N*-chloro- to an *N*-bromo-derivative, which should increase k_2 while leaving k_{-1} unaltered, has little or no effect on the product distribution (Tables 3, 4, and 6).

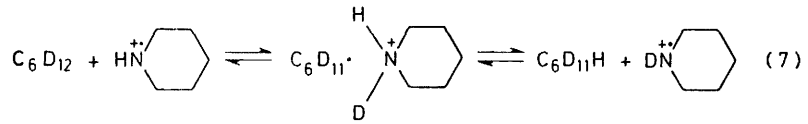
(2) In the photochlorination of hexane by *N*-chlorodicyclohexylamine in TFA, the addition of protonated triethylamine (three-fold excess over the *N*-chloroamine) had no effect on the chlorohexane product distribution. Reversible hydrogen-atom abstraction would have been expected to lead to the formation of triethylaminium radicals and hence to a change in the product distribution towards that obtained with this tertiary radical cation.

(3) When a three-fold excess of hexane was chlorinated with the *N*-chloro-derivative of trimethylamine, triethylamine, or 1-azabicyclo[2.2.2]octane in [^{2}H]TFA, a small amount of deuterium incorporation into the hexane (<5% based on the yield of chlorohexanes) was observed. It was reasoned that the protonated amine, present in the starting mixture and formed as a reaction product, would be deuteriated by exchange with the solvent and this in turn would lead to deuteriated hexane by reverse of step 1. The low value for deuterium incorporation suggests that the reverse reaction is unimportant unless it occurs predominantly between species held in a solvent cage [reaction (6)].

$$C_6H_{14} + R_3N^{+\bullet} \longrightarrow \underset{\text{solvent-caged species}}{[C_6H_{13}\cdot R_3\overset{+}{N}H]} \longrightarrow C_6H_{13}\cdot + R_3\overset{+}{N}H \quad (6)$$

(4) When a two-fold excess of [$^2H_{12}$]cyclohexane was chlorinated with *N*-chloropiperidine in TFA, the yield of [$^2H_{11}$]chlorocyclohexane was >95%. Analysis (combined g.l.c.–mass spectrometry) showed that there had been no detectable loss of deuterium from the unchanged substrate or the product. A reversible hydrogen-atom abstraction by the piperidinium radical, whether constrained within a solvent cage or not, would have been expected to show an incorporation of hydrogen into both substrate [reaction (7)] and, consequently product.

If reversible hydrogen atom-abstraction occurs in these alkane halogenations it evidently cannot compete



(7)

effectively with trapping of the alkyl radicals by the *N*-halogeno-compounds. Consequently the selectivities of aminium radicals for different C–H bonds, which can be measured directly from halogenoalkane product distributions, must be attributed to steric effects super-

imposed on the expected preference for secondary over primary C–H bond cleavage that is related to the difference in bond dissociation energies.

Attempts to halogenate hexane with *N*-halogenoammonium salts more highly hindered than those reported above were unsuccessful. In some instances the amines were too highly hindered or unreactive for the preparation of the *N*-halogeno-derivative (*e.g. NN*-2,6-tetramethylaniline) and in others the aminium radical was so hindered that hydrogen atom-abstraction was unable to compete effectively with the other reactions of these radical cations.

Primary Kinetic Isotope Effects and the Nature of the Transition State for Hydrogen-atom Abstraction.—In a series of competitive experiments a large excess of cyclohexane and [$^2H_{12}$]cyclohexane was photochlorinated in TFA. The yields of the products, chlorocyclohexane and [$^2H_{11}$]chlorocyclohexane, were measured by g.l.c. and in some instances also by ^{13}C n.m.r. and the results were used to calculate the primary isotope effect (k_H/k_D) for hydrogen-atom abstraction (Table 8). Corey and

TABLE 8

Kinetic isotope effects for the photochlorination of cyclohexane and [$^2H_{12}$]cyclohexane and the selectivity for the photochlorination of the 2- and 3-positions of hexane in TFA at 5 °C

Chlorinating agent	Ratio of yields of 2- and 3-chlorohexanes	Kinetic isotope effect (k_H/k_D)
Chlorine	1.0	1.7
N-Chloropiperidine	2.0	3.3
N-Chloro-1-azoniabicyclo[2.2.2]-octane perchlorate	2.0	3.5
N-Chlorotrimethylammonium perchlorate	2.5	3.5
N-Chlorotriethylammonium perchlorate	3.8	3.9
N-Chloro-2,2,6,6-tetramethylpiperidine	4.1	5.5
N-Chlorodimethyl-t-butylammonium perchlorate	4.5	4.5
N-Chlorodi-isopropylmethylammonium perchlorate	4.7	3.7

Hertler,[17] in their study of the Hofmann–Löffler reaction, found k_H/k_D 3.5 for the intramolecular hydrogen-atom abstraction by the aminium radical derived from [4-$^2H_1$]-*N*-chloropentylmethylamine in sulphuric acid at 95 °C. The corresponding value at the temperature of our experiments would be expected [18] to be *ca.* 6, and this is comparable with the largest values we found although it is somewhat less than the predicted maximum isotope effect at 5 °C, *ca.* 8.[18]

The observed variation in k_H/k_D with the chlorinating agent was reproducible and was shown not to arise from selective further reaction of the products. With *N*-chlorodi-isopropylmethylammonium and *N*-chloro-t-butyldimethylammonium perchlorate the chlorinating agents were divided into two; half were used for kinetic isotope studies and half for chlorinating hexane. In this way two of the chlorinating agents were checked and shown to give the expected selectivity in hexane chlorinations.

As we have shown above, increasing the bulk of the aminium radical increases its relative selectivity for hydrogen abstraction from the 2- compared with the 3-position of hexane. It also seems likely that increased steric crowding for these processes results in increased C–H bond breakage in the transition state and that this is the cause for the dependence of the magnitude of the kinetic isotope effect on the attacking radical cation. That the isotope effect does not increase with the extent of C–H bond cleavage in the transition state but passes through a maximum value agrees well with the theory of Westheimer.[19] Thus for reactions such as chlorination with chlorine atoms, where the transition state occurs early in the reaction profile, corresponding to little C–H bond breakage, k_H/k_D is small. As the extent of C–H bond cleavage increases and the transition state occurs later in the reaction profile, k_H/k_D should increase to a maximum value and then decrease to a small value where the C–H bond is almost completely broken. Thus for aminium radicals the transition state for C–H bond cleavage evidently moves from being relatively early for the piperidinium radical to being late for the di-isopropylmethylaminium radical. For the reaction with 2,2,6,6-tetramethylpiperidinium radical k_H/k_D is largest and the transition state for this process must have a near-central position in the reaction profile.

EXPERIMENTAL

^1H N.m.r. spectra for deuteriochloroform and TFA solutions were obtained with a Perkin Elmer R10, Varian A-60A, or JEOL 100 MHz spectrometer and ^{13}C n.m.r. spectra with a JEOL JNM-FX60 Fourier transform spectrometer. Tetramethylsilane was used as internal standard. Routine low-resolution mass spectra were measured on an A.E.I. MS12 or MS30 spectrometer. G.l.c. analysis was carried out with a Pye series 104 or Pye-Unicam GCD chromatograph with a flame-ionisation detector. Preparative g.l.c. used a Pye series 105 chromatograph. The following packing materials were used: Porasil C (120—150 mesh, Waters Associates) for bromohexanes, Porasil C–n-octane 'Durapak' (120—150 mesh, Waters Associates) for chlorohexanes, and 10 and 20% w/w MS550 silicone oil (B.D.H. Ltd.) on 80—120 mesh Celite for chloro-2-methylbutanes and polyhalogenated compounds. A commercial stainless steel capillary column (20 m × 0.2 mm i.d.) coated with silicone oil MS710 (Perkin Elmer Ltd.) was used to separate chlorocyclohexane and [$^2H_{11}$]chlorocyclohexane. Combined g.l.c.–m.s. used a Pye series 104 chromatograph coupled *via* a jet separator to the mass spectrometer.

Materials.—All the commercial materials were of reagent grade unless otherwise stated and were obtained from Aldrich Chemical Co. Ltd., B.D.H. Ltd., Koch–Light Ltd., Fisons Scientific Apparatus Ltd., or Fluorochem. Ltd. The nitrogen gas (British Oxygen white spot) was dried by passing it through concentrated sulphuric acid followed by silica gel and potassium hydroxide pellets. Hexane was g.l.c. grade (B.D.H. Ltd.), [$^2H_{12}$]cyclohexane was gold label (99.5% deuteriated, Aldrich Chemical Co. Ltd.), and iron(II) sulphate heptahydrate was AnalaR grade (Fisons Scientific Apparatus Ltd.).

Authentic chloroalkanes that were not commercially available were prepared from the corresponding alcohols with sulphur dichloride oxide following the procedure of Vogel [20] and had satisfactory b.p.s [21] and n.m.r. spectra. Bromohexanes were prepared from the alcohol with hydrobromic acid by the procedure of Vogel [22] and had satisfactory b.p.s [21] and n.m.r. spectra. The purity of all the halogenoalkanes was checked by g.l.c. [$^2H_{11}$]Chlorocyclohexane was prepared by the photochlorination of [$^2H_{12}$]-cyclohexane with chlorine in tetrachloromethane and the product was purified by preparative g.l.c. Tetrachloromethane was purified by the procedure of Vogel.[23] [^{2}H]TFA was prepared by the reaction of trifluoroacetic anhydride with deuteriated water (99%; Ryvan Chemical Co. Ltd.) and was purified by distillation. No measure of the deuterium content was made.

Amine precursors of *N*-halogeno-compounds that were not available commercially were prepared as described below. Dimethyl-t-butylamine, b.p. 91—92 °C (lit.[24] 90 °C at 740 mmHg), *cis*-1,2,6-trimethylpiperidine, b.p. 143—146 °C (lit.[21] 143 °C at 744 mmHg), 1,2,2,6,6-pentamethylpiperidine, b.p. 180—183 °C (lit.,[25] 182—185 °C), and di-isopropylmethylamine, b.p. 118—120 °C (lit.,[26] 109—112 °C), were prepared by methylation of the corresponding primary or secondary amine by the method of Clarke *et al.*,[27] and *NN*-2,6-tetramethylaniline, b.p. 195—197 °C (lit.,[28] 194—199 °C), by methylation of 2,6-dimethylaniline following Borkowski and Wagner.[28] Tri-isopropylamine was prepared following Kuffner and Koechlin [29] and had b.p. 135—137 °C (lit.,[29] 139 °C). *N*-Methyl-9-azabicyclo[3.3.1]-nonane was obtained from pseudopelletierine [30] by the Huang-Minlon modification of the Wolff–Kishner reduction following Leonard and Morrow.[31] The tertiary amine was purified as its perchlorate salt (Found: C, 44.9; H, 7.4; N, 5.8. Calc. for $C_9H_{18}ClNO_4$: C, 45.1; H, 7.6; N, 5.8%).

N-Bromo- and *N*-chloro-dimethylamine and *N*-chloro-piperidine were prepared following Spanswick and Ingold.[15b] The last compound had b.p. 30 °C at 7 mmHg (lit.,[15b] 42 °C at 12 mmHg) and ^{1}H n.m.r. spectroscopy of TFA solutions showed that none of these contained any protonated parent amine. *N*-Chlorodi-isopropylamine and *N*-chlorodicyclohexylamine were prepared with *N*-chloro-succinimide following Neale and Walsh [12] and were used without further purification. *N*-Chloro-2,2,6,6-tetramethylpiperidine was prepared following Deno *et al.*[7c] and had b.p. 100—101 °C at 35 mmHg (lit.,[32] 65 °C at 7 mmHg). *N*-Bromo-2,2,6,6-tetramethylpiperidine was prepared by the reaction of equimolar amounts of *N*-bromosuccinimide and 2,2,6,6-tetramethylpiperidine in dry diethyl ether. After 3 h the insoluble succinimide was removed by filtration and the filtrate was washed with water and then dried ($MgSO_4$). Removal of the solvent under reduced pressure at room temperature gave the *N*-bromoamine. Attempts to purify the material further by distillation resulted in decomposition.

N-Chloroammonium perchlorates were prepared by a modification of the method of Böhme and Krause [10] in which a cooled solution (−20 °C) of the tertiary amine (5 mmol) in tetrachloromethane (5 cm^3) was added dropwise, with stirring, to tetrachloromethane (10 cm^3) saturated with chlorine at −20 °C. The *N*-chloroammonium chloride which was formed as a precipitate was dissolved in TFA at the same temperature and the acid layer was separated from tetrachloromethane. The TFA solution was then stirred with excess of silver perchlorate and the silver chloride obtained was removed by filtration to give a clear solution of the *N*-chloroammonium perchlorate in TFA. The *N*-chloroammonium salts of 1-azabicyclo[2.2.2]octane and *N*-methyl-9-azabicyclo[3.3.1]nonane were synthesised as described above except that the free amines had first to be liberated from the ammonium salt with aqueous base and extracted into tetrachloromethane. The preparations of the *N*-chloroammonium salts of 1,2,2,6,6-pentamethylpiperidine and *NN*-2,6-tetramethylaniline were attempted using the method described above with a variety of temperatures and a range of solvents (CH_2Cl_2, $CHCl_3$, and CCl_4), but each was unsuccessful. *N*-Bromo-ammonium salts were prepared in an analogous way to the *N*-chloroammonium salts with bromine in place of chlorine; however, none of the *N*-bromoammonium salts was stable in TFA. *N*-Bromo-1-azoniabicyclo[2.2.2]octane perchlorate was prepared by isolating the solid *N*-bromo-ammonium bromide (prepared as above) from tetrachloro-methane by filtration, dissolving the solid in dichloro-methane, and stirring the solution with excess of silver perchlorate at 0 °C for 30 min. Filtration followed by removal of solvent under reduced pressure at <0 °C gave an orange solid that was dissolved in TFA at 0 °C.

^{1}H N.m.r. absorption data for the *N*-halogenoammonium perchlorates are in Table 9. The concentrations of solutions of the *N*-halogenoamines were estimated by measuring the amount of iodine liberated from accurately measured portions with standardised sodium thiosulphate solution and B.D.H. ' Iodine indicator '. The concentration of the TFA solutions of *N*-halogenoammonium salts were estimated by ^{1}H n.m.r. spectroscopy using known amounts of

TABLE 9

^{1}H N.m.r. data for *N*-chloroammonium perchlorates in TFA

N-Chloro-derivative of	Chemical shifts (δ) NMe	α-CH	β-CH	γ-CH	Other
Trimethylamine	4.0 (s)				
Triethylamine		4.5 (q, 6 H)	1.65 (t, 9 H)		
Tri-isopropylamine		4.7 (h, 3 H)	1.6 (d, 18 H)		
Dimethyl-t-butylamine	3.9 (s, 6 H)		1.8 (s, 9 H)		
Di-isopropylmethylamine	3.6 (s, 3 H)	4.4 (m, 2 H)	1.7 (m, 12 H)		
N-Methylpiperidine	3.9 (s, 3 H)	3.8br (t, 4 H)	2.3br (m, 6 H)		
N-Methylmorpholine	4.1 (s, 3 H)	4.6br (m, 8 H)			
1-Azabicyclo[2.2.2]octane		4.2 (m, 6 H)		2.3 (m, 7 H)	
1-Azabicyclo[2.2.2]octane [a]		4.3 (m, 6 H)		2.4 (m, 7 H)	
cis-1,2,3-Trimethylpiperidine [b]	3.5 (s,) 3.8 (s,) } 3 H	4.0 (m, 2 H)		2.0 (m, 6 H)	1.7 (d,) 1.9 (d,) } 6 H

[a] N-Bromoammonium perchlorate. [b] Two isomers present in the ratio of 4 : 1.

tertiary amine and assuming all the amine was present either as *N*-halogenoammonium salt or protonated amine.

Reactions.—(i) *Dark reactions.* A solution of the *N*-chloroammonium salt (prepared from 5 mmol tertiary amine) in TFA (10 cm^3) was stirred with hexane (10 cm^3) in a stoppered flask under nitrogen in the dark at the required temperature. After a set time the mixture was poured into water (25 cm^3) and the alkane layer was analysed by g.l.c. with 1-chloropentane as an internal standard.

(ii) *Photohalogenations.* The reactions were carried out in a cylindrical glass or quartz reaction vessel which was cooled with an external water jacket and illuminated externally [300 W quartz halogen lamp (Thorn type A1/240), 100 W high pressure mercury arc u.v. lamp, or 1 kW xenon arc u.v. lamp]. The water coolant was cooled in an ice-bath prior to entering the jacket. The *N*-halogenoamine (5 mmol) or *N*-halogenoammonium perchlorate (prepared from 5 mmol tertiary amine) in TFA (10 cm^3) with alkane (10 cm^3) and a measured quantity of chloropentane (standard) was deoxygenated with nitrogen and then photolysed while the mixture was agitated with a stream of nitrogen bubbles. During the reaction small portions of the hexane layer were removed and analysed by g.l.c. When the reaction had ceased the products were worked up and analysed as described above.

(iii) *Photohalogenations in* [^{2}H]*TFA or in the presence of a large excess of ammonium ions.* These photohalogenations were carried out as described above with a glass reaction vessel and the 300 W visible light source. The reaction in [^{2}H]TFA used less hexane (2 cm^3) than the standard procedure. The reactions were worked up and analysed (g.l.c. and g.l.c.–m.s.) when all the *N*-halogeno-compound had been consumed (KI test).

(iv) *Photohalogenation of* [$^2H_{12}$]*cyclohexane with* N-*chloropiperidine.* [$^2H_{12}$]Cyclohexane (10 mmol) and *N*-chloropiperidine (5 mmol) were dissolved in TFA (15 cm^3) and deoxygenated with nitrogen, and the glass reaction vessel was sealed. Photolysis with the visible light source was continued until all the *N*-chloro-compound had been consumed (KI test) and the mixture was worked up and analysed (g.l.c. and g.l.c.–m.s.). For ^{1}H n.m.r. analysis of the proton content of the product, extraction was with deuteriochloroform and toluene was used as an internal standard.

(v) *Kinetic isotope effect experiments.* Accurately measured quantities of [$^2H_{12}$]cyclohexane and cyclohexane (*ca.* 2 mmol of each) were dissolved in TFA (15 cm^3) and photolysed with the *N*-halogeno-compound (0.2 mmol) as described above for [$^2H_{12}$]cyclohexane. After photolysis the mixture was poured into water (25 cm^3) and extracted either into deuteriochloroform (for ^{13}C n.m.r. analysis and g.l.c. analysis) or into hexane (for g.l.c. analysis alone).

Chlorocyclohexane has δ_C 60.2 (C-1), 36.7 (C-2), 25.2 (C-4), and 24.9 p.p.m. (C-3) and [$^2H_{11}$]chlorocyclohexane has δ_C 59.6 (t, *J* 23.2 Hz, C-1), 38.3 (q, *J* 19.6 Hz, C-2), and 28.3—22.5 p.p.m. (m, C-3 and -4). It was shown, using synthetic mixtures of the two compounds, that integration of the signals from C-1 and -2 could be used to determine the relative amounts of deuteriated and undeuteriated chlorocyclohexane. The interval between the pulses of the Fourier transform spectrometer was kept long (typically 10 s) or a small quantity of $Cr(acac)_3$ was added to the sample to avoid saturation of the signals. Product ratios from competitive chlorinations of cyclohexane and [$^2H_{12}$]-cyclohexane measured by ^{13}C n.m.r. agreed well with those obtained from g.l.c. analyses.

(vi) *Photohalogenations with free halogen.* The photolyses were carried out and worked up as described above for the general procedure except that a halogen-saturated solution of TFA was used in place of the *N*-halogeno-compound in TFA.

(vii) *Redox-initiated halogenations.* A solution of the *N*-chloro-compound (5 mmol) in TFA (10 cm^3) was vigorously stirred with the alkane (10 cm^3) in the dark under nitrogen while iron(II) sulphate (5 mmol) was added either as a fine powder in one portion or dropwise as a concentrated aqueous solution. The mixture was worked-up when all the *N*-chloro-compound had been consumed.

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