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On the Reaction of *N*-Bromoacetamide with Olefins. Preparation and Chemistry of 2-Bromo-*N*-Bromoacetimidates, a New Class of Compounds[1]

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A historical and mechanistic review of the Wohl–Ziegler reaction (allylic bromination by *N*-bromoamides and imides) is presented as an introduction to the present work, a re-examination of the reaction of *N*-bromoacetamide (NBA) with some olefins. The reaction has been found to lead not to allylic bromination but, rather, to 2-bromo-*N*-bromoacetimidates, a new class of compounds. The stoichiometry of the reaction is: olefin + 2 NBA → adduct + acetamide. The process appears to occur in two stages, *viz.*, a free radical reaction of NBA with itself to form *N,N*-dibromoacetamide (NDBA), followed by ionic addition of NDBA to the double bond. Hofmann's synthesis of NDBA has been repeated; the compound reacts rapidly with cyclohexene to give the same adduct **10** as does NBA. A variety of stereochemical and selectivity data suggest that this is an ionic addition.

The chemical transformations of 2-bromo-*N*-bromoacetimidates under thermal, acidic, and basic conditions are discussed.

Comme introduction au présent travail qui est un réexamen de la réaction de la *N*-bromoacétamide avec quelques oléfines, nous présentons une revue historique et mécanistique de la réaction de Wohl–Ziegler (bromuration allylique par des *N*-bromoamides et imides). On a trouvé que la réaction ne conduit pas à la bromination allylique mais plutôt aux bromo-2 *N*-bromoacétimidates, une nouvelle classe de composés. La stoichiométrie de la réaction est: oléfine + 2 NBA → composé d'addition + acétamide. Le processus semble se produire en deux temps à savoir une réaction radicalique de la NBA sur elle-même pour conduire à la *N,N*-dibromoacétamide (NDBA) suivie d'une addition ionique de la NDBA à l'alcène. La synthèse de Hofmann de la NDBA a été repétée; ce composé réagit rapidement avec le cyclohéxène et conduit au produit **10** qui est aussi obtenu sous l'action de la NBA. La stéréochimie et la sélectivité de cette réaction suggèrent que l'addition est ionique.

On discute aussi des transformations chimiques que subissent les bromo-2 *N*-bromoacétamidates sous l'influence de la chaleur, des acides, et des bases.

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Historical Introduction

In 1919, A. Wohl reported (1) that a mixture of 10 g of tetramethylethylene and 16 g of *N*-bromoacetamide (NBA), allowed to stand overnight in 36 ml of ether and then distilled, afforded in 16% yield a bromine-containing fraction, b.p. 60–90° at 15 mm. This liquid decolorized permanganate and contained 46.3% of bromine ($C_6H_{11}Br$ requires 49.0% bromine). A mixture of 50 g of trimethylethylene and 100 g of NBA, allowed to stand for one day and then vacuum distilled, afforded 10 g of an oil, b.p. 49–52.5° at 13.5 mm, which decolorized permanganate and contained 67.6% of bromine (C_5H_9Br requires 53.6%, and $C_5H_8Br_2$ requires 70.1% bromine). On the basis of these results, Wohl formulated the latter substance as an unsaturated dibromide, $C_5H_8Br_2$, and the product from tetramethylethylene as an unsaturated monobromide, $C_6H_{11}Br$, the reaction in this instance being described by eq. 1. A mechanism was proposed which involved exchange of bromine for an allylic hydrogen within a 1:1 olefin-NBA complex. The possibility that this complex

[1] $Me_2C{=}CMe_2 + CH_3CONHBr \rightarrow Me_2C{=}CMeCH_2Br + CH_3CONH_2$

might be an intermediate in an addition–elimination sequence was considered, and rejected on the grounds that HBr, rather than acetamide, ought to have been eliminated from such an adduct.

When equal amounts of NBA and trimethylethylene were mixed in ether at low temperature, the sparingly soluble NBA slowly dissolved and a viscous oil precipitated. The supernatant solution was then found to contain only traces of olefin and NBA. Wohl recognized that the viscous oil was an addition compound, but

[1]This work was presented, in part, at the 50th Canadian Chemical Conference, Toronto, Ontario, June 1967.

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apparently believed that its formation was not related to the reactions which produced the unsaturated dibromide.

In a second paper in 1921 (2), Wohl and Jaschinowski extended this work to the substrates crotonic acid, ethyl β-ethoxycrotonate, ethyl β-ethoxycinnamate, propylene, allyl alcohol, allyl bromide, and methyl phenylacetylene. In each case the reactants were stirred in ether or acetone at room temperature or below until a negative starch–iodide test was obtained; products were then isolated by vacuum distillation and characterized by bromine analysis. Carbon and hydrogen analyses were recorded for the products from the enol ethers and from allyl alcohol. In all cases, the distilled sample subjected to analysis represented only a small fraction of an obviously complex mixture; in several cases the analytical data were not compatible with a simple molecular formula.

Wohl and Jaschinowski observed that 2 mol equiv of NBA reacted with 1 mol equiv of crotonic acid to produce a *mono*bromocrotonic acid. They also observed some yellow crystals in the reaction with propylene. Neither of these observations was followed up. Ethylene, acetylene, ethyl cinnamate, cinnamic acid, cinnamaldehyde, maleic acid, and fumaric acid did not react with NBA. Styrene gave styrene dibromide.

It is evident from this summary of Wohl's experimental work that, although some reaction does take place between certain olefins and NBA, unequivocal evidence for allylic bromination was not obtained. It is not surprising, therefore, that the next reference to this work appeared only in 1941 (3). An attempt to convert β-cyclogeranic acid to 3-bromo-β-cyclogeranic acid was not successful.

In 1942 (4), Ziegler and his co-workers presented the results of a systematic study, prompted by Wohl's work, of the reactions of alkenes with *N*-halo compounds. *N*-Bromoacetamide was not included in the study because "*die von Wohl mitgeteilten Ergebnisse auf einem nicht eben glatten Reaktionsverlauf schliessen lassen*". In Ziegler's work the unique ability of *N*-bromosuccinimide (NBS), in refluxing carbon tetrachloride, to effect allylic bromination was discovered and exploited. The synthetic implications of this discovery were very clear and, by 1948 (5), at least 100 examples had been reported. Djerassi's review, subtitled "The Wohl–Ziegler Reaction", left the impression that Wohl's work had been overlooked because of a failure to emphasize its practical implications, and the description "Wohl–Ziegler reaction" is taken to mean allylic bromination by *N*-bromoamides and imides, including NBA and NBS. Although allylic bromination by NBA has often been assumed since the appearance of the first review, in no case do the experimental descriptions indicate that an allylic bromide was ever isolated and characterized. Indeed, the work reported here was also founded on the assumption that allylic bromination by NBA does exist; and a close examination of Wohl's papers was not made until it had become clear (6) that this assumption is incorrect.

Introduction to the Present Work

That allylic bromination by NBS is a radical chain reaction is evident from the catalytic effect of peroxides, other radical sources, and u.v. light, the retarding properties of oxygen and other typical radical inhibitors (7), and kinetic studies (8). In allylic bromination of cyclohexene, initiated by decomposition of azobisisobutyronitrile (AIBN), the rate of disappearance of NBS is zero order in NBS, half order in AIBN and first order in olefin. This result is consistent with a succinimidyl radical chain and termination via two succinimidyl radicals. It is also consistent with a bromine atom chain and termination via two bromine atoms. The former pathway, proposed by Bloomfield in 1944 (9), was widely accepted for some time (7), but more recent work (10–13) has proved the latter process, first suggested by Goldfinger and his co-workers (14), to be the operative one.

The Goldfinger mechanism considers the elementary steps 2–5, where RH is an alkene. For low concentrations of X_2, the ratio of addi-

[2] $Br_2 \rightarrow 2Br\cdot$

[3s] $Br\cdot + HR \rightarrow HBr + R\cdot$ [3a] $Br\cdot + RH \rightarrow Br\dot{R}H$

[4s] $R\cdot + Br_2 \rightarrow RBr + Br\cdot$ [4a] $Br\dot{R}H + Br_2 \rightarrow BrRHBr + Br\cdot$

[5s] $R\cdot + HBr \rightarrow RH + Br\cdot$ [5a] $Br\dot{R}H \rightarrow RH + Br\cdot$

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tion (*a*) to substitution (*s*) is given by eq. 6 so

[6] $$r_{a/s} = k_{3a} \cdot k_{4a}[Br_2] / k_{3s} \cdot k_{5a}$$

that addition would be favored by higher, and substitution by lower concentrations of Br_2. The function of NBS is two-fold: to maintain the required low concentration of Br_2 by reaction 7 (10); and, by serving as a scavenger for HBr, to maintain a non-polar medium.

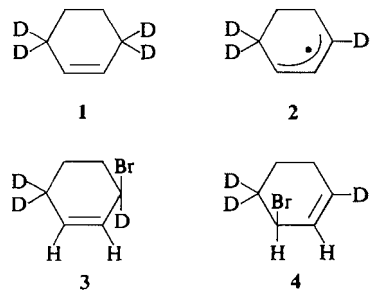
[7] $$HBr + NBS \rightarrow Succinimide + Br_2$$

Two significant features of allylic bromination by NBS are that both NBS (15) and succinimide are virtually insoluble in CCl_4, the solvent of choice for the reaction, and that the rate of the reaction depends greatly upon the purity of the reagent and its surface area. High purity and/or the employment of large crystals lead to a reduction in the rate (8, 16). These facts have led Horner and Winkelmann to suggest (16) that the reaction takes place at the surface of the NBS, but an alternate explanation (8*a*) for the rate-diminishing effect of purification of the reagent is that this removes trace impurities which catalyze the adventitious formation of molecular bromine, and the surface mechanism is usually discounted (see *e.g.*, ref. 12*a*, footnote 28).

If the surface mechanism were unimportant, it could be expected that slow addition of a *solution* of NBS to an alkene might be equivalent to the usual heterogeneous reaction conditions. However, although addition to the double bond of cyclohexene is not detected under the heterogeneous conditions, when the reaction is performed in refluxing CH_2Cl_2 with slow addition of the NBS and catalysis by light and peroxides the conversion to dibromocyclohexane cannot be reduced to less than 25% (17).

Further, if there were no constraint upon the intermediates in the reaction, the mesomeric structure of an allyl radical should cause the product of kinetic control to be a mixture of two allyl bromides. In the case of a symmetrical substrate like cyclohexene-3,3,6,6-d_4 (**1**), the allyl radical will have structure **2**, and the products of kinetic control would be **3** and **4**, formed in equal amounts. It has been suggested, however, that an equimolar mixture of **3** and **4** is seen in the product of *thermodynamic* control, the product of kinetic control being mainly **3** (18). This result is not compatible with a "free" radical mechanism but might be compatible with a "trapped" radical if the surface mechanism were operative.

On the basis of the above results and considerations it appeared that Horner and Winkelmann's surface mechanism needed further examination. The approach selected involved repetition of the cyclohexene-3,3,6,6-d_4 experiment with NBA. It was assumed that NBA does effect allylic bromination and that the ratio of **3** to **4** in the product of kinetic control would differ from that given by NBS, either because NBA bromination affords a free radical, or because the surfaces of NBA and NBS are not the same. The choice of NBA for this study was also dictated by the fact that it, like NBS, is only slightly soluble in refluxing CCl_4 and was reported to effect allylic bromination in this medium (19–21).



Results and Discussion

Reaction of NBA with Cyclohexene

In refluxing carbon tetrachloride, NBA is a solid and is only slightly soluble. Acetamide, the expected product of allylic bromination, is soluble in refluxing CCl_4; therefore, dissolution of the insoluble solid provides a convenient visual assay of the progress of an NBA reaction under these conditions. When cyclohexene was allowed to react with NBA in refluxing CCl_4, with catalysis by light and peroxide, the NBA disappeared within 5 min. The g.l.c. analysis of the reaction mixture at this point revealed only *trans*-1,2-dibromocyclohexane (**5**) and, surprisingly, no 3-bromocyclohexene. Continued refluxing caused darkening of the solution, and in the g.l.c. two new peaks appeared. The relative amounts of the new compounds gradually increased and, after 1 h, on the basis of the areas under the three peaks, one of the new compounds represented about 55% of the

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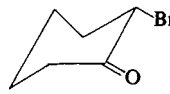
mixture and the other about 5%. The new compounds were isolated by preparative g.l.c. and identified as *trans*-cyclohexene bromohydrin (**6**; major product) and 2-bromocyclohexanone (**7**; minor product). Repetition of the experiment, with addition of benzonitrile as an internal standard for the g.l.c. analyses, revealed that **6** and 7 were not formed at the expense of **5** and confirmed that 3-bromocyclohexene was not present at any time. (It was established that 3-bromocyclohexene is stable to the reaction conditions and to the g.l.c. procedure employed.)

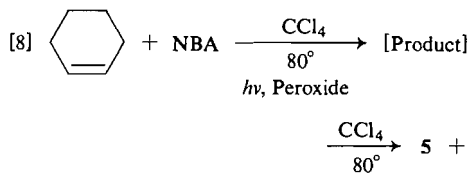
5

6



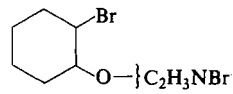
7

It seemed likely that **6**, especially, had been formed by thermal decomposition of a primary product of higher molecular weight or polarity whose retention time was too great to permit its detection under the g.l.c. conditions utilized. If **5** and **7** also were formed from this primary product, the course of the reaction could then be described tentatively as shown in eq. 8. For



the isolation of this primary product, the reaction of cyclohexene with one molar equivalent of NBA was terminated by rapid cooling as soon as the NBA had disappeared. Acetamide precipitated and was removed by filtration; evaporation of the filtrate under reduced pressure at 30° yielded a colorless oil. Treatment of this oil afforded, besides a small amount (*ca.* 1%) of *trans*-2-acetamidocyclohexyl bromide (**8**), massive crystals melting at 28.0–28.5°. Microanalysis indicated a formula $C_8H_{13}Br_2NO$, *i.e.*, an *adduct* of cyclohexene plus NBA plus Br minus H. In view of the nature of the products **5**–**7** a part structure **9** could be assigned, and the gross structure **10**, 2-bromocyclohexyl-*N*-bromoacetimidate, became clear upon examination of the i.r. and n.m.r. spectra (6). The i.r. spectrum showed strong absorption at 6.2 and 7.85 μ assigned, respectively, to the C=N and C—O—C groupings (22); the n.m.r. spectrum showed 1-proton multiplets at τ 4.96 and 5.87, a methyl peak at 7.62, and a cyclohexane envelope (8 protons) centered at 8.34. The stereochemistry of the addition to the double bond was determined to be *trans* by preparation and n.m.r. analysis of the adduct **11** of cyclohexene-3,3,6,6-d_4. This adduct showed an AB quartet (τ_A 4.96; τ_B 5.87) for the tertiary protons with a coupling constant of 9 Hz; the chemical shift assignments shown in **11** are based on comparison with those of cyclohexene-3,3,6,6-d_4 bromohydrin (18) (τ_{CHBr} 6.13; τ_{CHOH} 6.4) and its derived acetate (τ_{CHBr} 5.95; τ_{CHOAc} 5.2). The geometry of the C=NBr grouping of **10** was not investigated.

8



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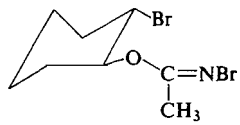
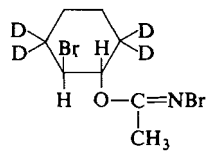


10



11

Because of its low m.p. no attempt was made to optimize the recovery of crystalline **10**. However, since the i.r. spectrum of the mother liquor obtained following removal of the first crop of **10** was superimposable upon that of **10**, it was concluded that **10** represented at least 90% of the non-volatile product of the primary reaction of equimolar amounts of cyclohexene and NBA. Since **10** contains two bromine atoms it seemed that at least 2 mol equiv of NBA per mol of alkene were necessary for the reaction. To check the stoichiometry, 0.5:1, 1:1, 2:1, 3:1, and 4:1 molar ratios of cyclohexene to NBA were allowed to react in refluxing CCl_4 with catalysis by light and peroxide. Each reaction mixture was rapidly cooled when the initial reaction was complete and the precipitated acetamide was collected and weighed; in each case this amounted to 90–95% of the theoretical based on eq. 9. Each filtrate was concentrated under reduced pressure and the distillate titrated with a standardized solution of Br_2 in CCl_4; except for the product from a

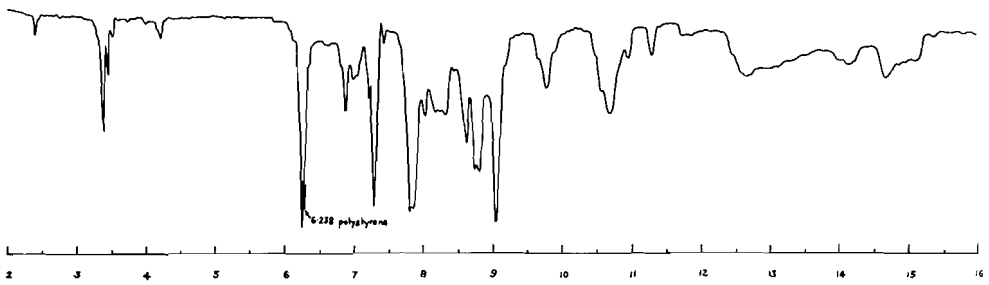


FIG. 1. The i.r. spectrum (KBr) of **12**.

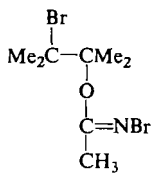
0.5:1 molar ratio of reactants, which contained no cyclohexene, all distillates contained cyclohexene in amounts corresponding to 80–100% of that expected on the basis of eq. 9. The nonvolatile residue was then weighed and its i.r. spectrum recorded; in each case these i.r. spectra were virtually identical with the spectrum of pure **10**. It can be concluded that the reaction of cyclohexene with NBA is not an allylic bromination but an addition, closely obedient to the stoichiometry shown in eq. 9, in which **10**, a new class of compound, is produced.

[9] Cyclohexene + 2 NBA → **10** + Acetamide

Reaction of NBA with Tetramethylethylene

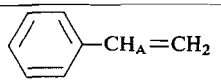
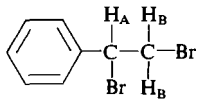
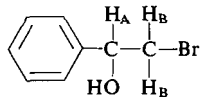
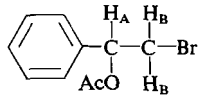
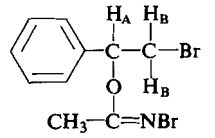
Since Wohl's initial experiment was performed with tetramethylethylene it was of interest to examine the reaction of this substrate with NBS employing the conditions and stoichiometry established for cyclohexene. A crystalline compound, m.p. 40–41°, was obtained. This compound analyzed as $C_8H_{15}Br_2NO$; its n.m.r. spectrum showed three methyl singlets, at τ 7.72, 7.99, and 8.17, in the ratio 1:2:2 and its i.r. spectrum, reproduced in Fig. 1, showed prominent peaks at 6.2 and 7.85 μ. All of these data are compatible with structure **12**, the 2-bromo-*N*-bromoacetimidate adduct of tetramethylethylene.

It was conceivable that the experimental conditions employed here, *viz.*, refluxing in CCl_4 in the presence of light and peroxide, had led to a reaction different from that envisaged by Wohl (1). To check this point, NBA was allowed to react with tetramethylethylene *in ether*. There was no reaction at 0° in the dark but, in 4.5 h at room temperature and in the diffuse light of the laboratory, a 75% conversion to **12** was achieved (*cf.* paragraph 2 of the Historical Introduction).



12

TABLE 1. Proton chemical shifts of some styrene derivatives (τ values)

Compound	τ_A	τ_B
	3.5	
	4.95	6.18
	5.33	6.7
	4.32	6.5
	4.15	6.57

Reaction of NBA with Styrene and with 1-Methylcyclohexene

The adducts **10** and **12** are produced formally by the addition of bromine and *N*-bromoacetimidyl moieties to the double bond. To establish

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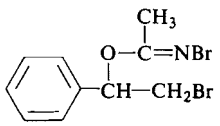
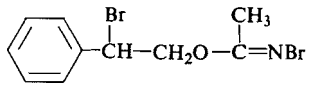
the sequence of these two additions it was necessary to determine the regioselectivity (23) of addition to unsymmetrical olefins. The styrene adduct is assigned structure **13** rather than **14** on the basis of the chemical shifts of its tertiary (triplet) and secondary (doublet) protons, comparison of these chemical shifts with those of the authentic styrene derivatives shown in Table 1, and the assumption that *N*-bromoacetimidate resembles acetate in its effect upon the chemical shift of a geminal proton. The 1-methylcyclohexene adduct was assigned structure **15** rather than **16** on the basis of the chemical shift data shown in Table 2. This structure and the formulation of the adduct as a product of *trans*-addition are supported by the chemical properties of the compound, described below.



13



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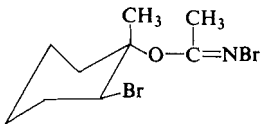
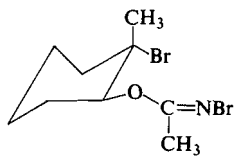


15



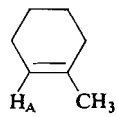
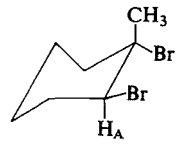
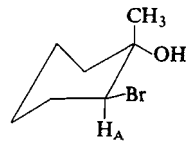
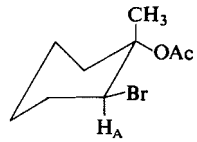
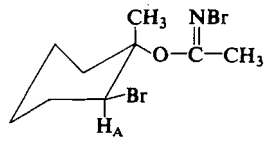
16

Mechanism of Formation of the Adducts

Adducts **13** and **15** contain bromine on the less-substituted carbon atom. Whether the addition of the two fragments is ionic (electrophilic) or radical, it follows that the C—Br bond is formed first. An ionic process for the addition seems more reasonable for the following reasons:

(*1*) Only the *trans*-adduct is obtained with cyclohexene. A radical addition reaction would have proceeded in a non-stereospecific manner. Thus, ionic chlorination of cyclohexene affords 1,2-dichlorocyclohexane which is at least 99% *trans* (24, 25) but, under radical conditions (25), the *cis* adduct is also observed, together with the products of vinylic, allylic, and homoallylic substitution. Similarly, ionic addition of bromine azide to cyclohexene and to 2-cholestene leads to the *trans*-adducts only; under radical conditions, the product from 2-cholestene is a 58:42 mixture of *trans* and *cis* adducts (26).

TABLE 2. Proton chemical shifts of some 1-methylcyclohexene derivatives

Compound	τ_A
	4.65
	5.4
	5.9
	5.3
	5.1

N,N-Dichlorourethane (DCU) adds to olefins by a free radical chain mechanism (27–29) to give 1:1 adducts **17**. With cyclohexene (27, 29) and cyclopentene (29) both *cis*- and *trans*-adducts are obtained together with the products of vinylic, allylic and homoallylic chlorination. Acyclic olefins react to give erythro–threo mixtures (27).

(*2*) Under ionic conditions, addition of IN_3 (26), ClN_3, and BrN_3 (30) to unsymmetrical olefins proceeds with attachment of halogen to the less substituted carbon atom, as in the present reaction. Under radical conditions the opposite regioselectivity is observed, *i.e.*, the *azido* group is attached to the less-substituted carbon atom. Similarly, in the radical addition of DCU, it is the nitrogen atom which becomes attached to the less-substituted carbon atom; *e.g.*, the styrene product is **18** (27).

(*3*) In the radical addition of DCU, as indi-

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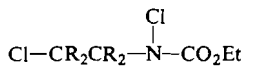
cated in **17** and **18**, a *nitrogen*–carbon bond is formed; in contrast, the addition reaction of NBA proceeds with formation of an *oxygen*–carbon bond.

(*4*) In a competition experiment involving reaction of NBA with a mixture of styrene and cyclohexene, only the cyclohexene adduct was formed. There is a variety of competition data which indicate that these two substrates display opposite selectivities in ionic and radical addition reactions (31). In a radical addition, styrene is several hundred times more reactive; and in an ionic addition, cyclohexene is five to ten times more reactive.

Although the final, adduct-forming stage of the NBA reaction with olefins thus appears to be ionic, the initial stage of the reaction is probably a free-radical chain process involving only the NBA. The over-all reaction is catalyzed by light and by peroxide. It is known (32) that u.v. irradiation of a refluxing solution of NBA in chloroform leads to rapid formation of a low equilibrium concentration of bromine. In the present work slow distillation of a refluxing suspension of NBA in carbon tetrachloride, illuminated by a 200 W bulb, led to the formation of bromine and acetamide in amounts compatible with the stoichiometry shown in eq. 10. Methyl isocyanate is indicated as a possible product of the decomposition, but attempts to detect this compound were not successful.

[10] $2NBA \rightarrow CH_3CONH_2 + Br_2 + [CH_3NCO]$

The elementary steps shown in eqs. 11–16 can be considered for the homolytic decomposition of NBA. The initiation step, eq. 11, must be followed by a rapid exchange, eq. 12 or eq. 13, which generates the *N*-bromoacetamidyl radical **19**. In each of these reactions there is a hydrogen abstraction *from NBA*; we believe that the availability of this hydrogen in NBA, and the absence of a reactive hydrogen in NBS,



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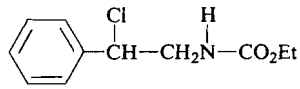


18

is a major source of the difference in behavior of the two brominating agents. Reaction **13** would be followed rapidly by 14 (10) and then 15, the latter being necessary to account for the failure to observe allylic bromide or dibromoolefin as primary products. The sequences 13–15 and 11, 12, 16 each lead to a compound $C_2H_3NOBr_2$ (**20**). Consideration of bond strengths (33) indicates that 16 would be strongly endothermic and 13–15 would be slightly exothermic.

It will be noted that addition of **20** to an olefin would afford a compound having the molecular formula of a 2-bromo-*N*-bromoacetimidate. Two structures can be considered for **20**, *viz.*, *N*,*N*-dibromoacetamide (**21**) and *N*,*O*-dibromoacetimide (**22**). A compound, assigned structure **21**, was prepared by Hofmann in 1882 (34) but no other reference to this substance could be found in the literature. Repetition of Hofmann's synthesis gave a yellow crystalline compound having the reported m.p. (100°) which analyzed correctly for $C_2H_3NOBr_2$. This compound is stable at room temperature in the solid state and as a solution in CH_2Cl_2 or $CHCl_3$. The n.m.r. spectrum in the latter solvent shows *one* singlet, at τ 7.50; in the same solvent the methyl protons of NBA appear as two singlets of unequal intensity at τ 7.8 and 8.0 (because of hindered rotation about the amide bond (35)). Acetamide shows a methyl singlet at τ 8.0. Thus the dibromo compound appears to exist in solution as a single species. Its constitution is clearly seen to be **21** (NDBA) rather than **22**

[11] $CH_3CONHBr \rightarrow CH_3CONH\cdot + Br\cdot$

[12] $CH_3CONH\cdot + CH_3CONHBr \rightarrow CH_3CONH_2 + CH_3\dot{C}ONBr$

19

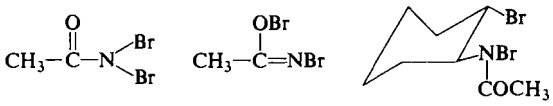
[13] $Br\cdot + CH_3CONHBr \rightarrow HBr + CH_3\dot{C}ONBr$

[14] $HBr + CH_3CONHBr \rightarrow Br_2 + CH_3CONH_2$

[15] $Br_2 + CH_3\dot{C}ONBr \rightarrow Br\cdot + [CH_3CONBr]\cdot Br$

20

[16] $CH_3\dot{C}ONBr + CH_3CONHBr \rightarrow CH_3CONH\cdot + [CH_3CONBr]\cdot Br$



21 22 23

when the solution i.r. spectrum is compared to those of NBA and acetamide. Carbonyl stretching bands are observed for acetamide, NBA and NDBA at 5.95, 5.94, and 5.92 μ, respectively; and NDBA shows a strong band at 8.2 μ (N—Br?) approximately twice the intensity of a band at the same position in NBA.

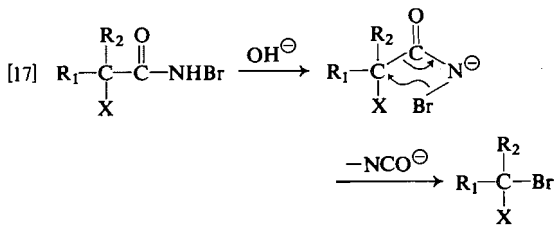
In methylene chloride or carbon tetrachloride solutions, at 0 or 25°, **21** reacted rapidly with cyclohexene to give a greater than 9/1 mixture of **10** and the isomeric compound **23**, the latter being isolated as the hydrolysis product **8**. The addition proceeded smoothly, and the ratio of the two adducts was not significantly different, both in the dark and in the light of the laboratory. It is evident, therefore, that the reaction of this olefin with NBA can be discussed in terms of a radical reaction of NBA with itself to produce NDBA, followed by an ionic addition of the latter to the double bond. An as yet unexplained feature of the addition reaction is the formation of a C—O bond (to form **10**) in preference to a C—N bond (to form **23**). This point is under investigation and will be reported later along with the detailed discussion of the spectral and chemical properties of NDBA (36).

Reactions of 2-Bromo-*N*-bromoacetimidates

Rearrangement to Dibromides

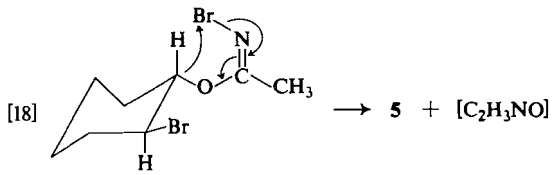
One of the differences that had been noted previously in the reactions of NBA and NBS with olefins (2, 17*b*, 20, 37, 38) was the much greater tendency of NBA to give dibromo addition compounds. The observations recorded in eq. 8 indicate that these may form during the thermal decomposition of 2-bromo-*N*-bromoacetimidates. Thus, when heated at 100° in the absence of a solvent, **10** underwent violent decomposition to give *trans*-dibromocyclohexane (30%) and other (tarry) products. Following injection of a solution of pure **10** into a gas chromatograph at 130°, only *trans*-dibromocyclohexane was detected. Refluxing of a 10% solution of **10** in carbon tetrachloride caused complete decomposition in 1 h. Even at room temperature, in the absence of a solvent, crystalline **10** decomposed completely in 18 h; g.l.c. analysis of the product of this decomposition revealed the ratio of cyclohexene bromohydrin to cyclohexene dibromide to be 3:1. If the crude product of the NBA–cyclohexene reaction was similarly left to decompose at room temperature an identical ratio of **6** to **5** was observed. These observations demonstrate that the dibromide is indeed a product of the decomposition of **10**; and the latter result indicates further that *all* of the dibromide is produced during this decomposition.

In dimethylformamide, at 100°, **10** decomposed to give (by g.l.c.) a 35:25:40 mixture of **5**:**6**:**7**. The proportions of these three compounds were unchanged, and no bromochlorocyclohexane was formed, when this experiment was repeated in the presence of a molar equivalent of lithium chloride. This result is consistent with the description of the conversion of **10** to **5** as an intramolecular rearrangement. The presence of **5** and the absence of *dibromocyclopentane* in the products of decomposition of **10** in refluxing cyclopentene (b.p. 44°) support the conclusion that **5** is the result of an intramolecular rearrangement. There appears to be a formal analogy between the nature of this rearrangement and base-catalyzed rearrangements of *N*-bromoamides, in which retention of configuration is also observed (39–43), see eq. 17. Following this



[17]

analogy, the conversion of **10** to **5** may be postulated to proceed by eq. 18. Methyl isocyanate



[18]

was considered to be a possibility for the species C_2H_3NO, by rearrangement of an acyl nitrene, but all attempts to isolate or trap the isocyanate were unsuccessful. It is relevant to note that recent investigations of the Curtius and Lossen rearrangements (44, 45) demonstrate that an isocyanate is formed from an acyl *azide*

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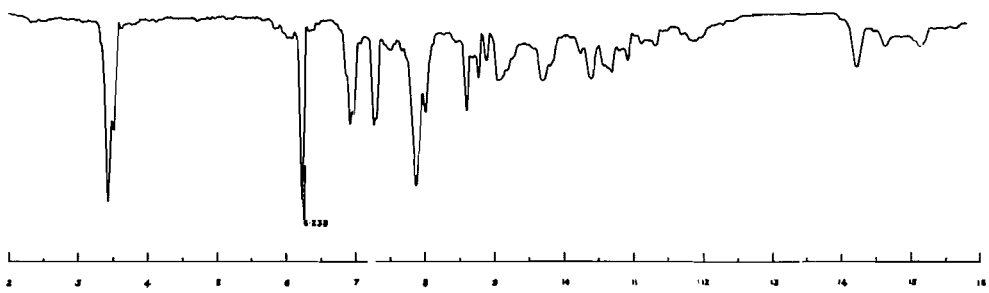

FIG. 2. The i.r. spectrum (KBr) of **15**.

in a concerted manner, intramolecular rearrangement of an acyl nitrene being much slower than intermolecular insertion, addition and abstraction reactions.

The rearrangement of a 2-bromo-*N*-bromoacetimidate to a dibromide just described is a general reaction of the adducts. After 60 h in ether at −20°, the styrene adduct had undergone 34% conversion to styrene dibromide. In chloroform at 30° this adduct decomposed completely within 1 h to give a mixture containing 30–40% of styrene dibromide. The 1-methylcyclohexene adduct was even less stable. The i.r. spectrum of **15** immediately after isolation is shown in Fig. 2; after 15 min in CCl_4 the peaks at 6.2 and 7.85 μ had disappeared completely. When this decomposition was followed by n.m.r., the disappearance of the tertiary proton absorption of **15** (τ 5.1) coincided with the appearance of peaks of equal intensity at τ 5.4 and 5.9, corresponding to 1-methylcyclohexene dibromide and 1-methylcyclohexene bromohydrin, respectively. In the reaction of NBA with stilbene, the adduct could not be detected; only stilbene dibromide (38%) was identified among the products of this reaction.

Reaction with HCl

In the investigations of Buckles *et al.* of the reaction of olefins with NBA (20, 37, 38), it was assumed that dibromides were primary products. This assumption caused some difficulty in the establishment of a stoichiometry. The reaction was clearly seen to be radical in nature, and acetamide was a product, but there was no obvious source of hydrogen to account for the formation of this compound or for the fate of the acetamidyl radical. In an attempt to optimize the recovery of the acetamidyl fragment, the product of the styrene reaction (0.1 mol of NBA to 0.05 mol of styrene) was treated with anhydrous hydrogen chloride (20); a precipitate was obtained and identified as bisacetamide hydrochloride on the basis of a "m.p. around 131°" (pure acetamide hydrochloride was also found to have "m.p. around 131°"). On the assumption that the precipitate had this structure, a 95–97% recovery of acetamide was claimed.

If this observation were correct, it would follow from the stoichiometry of the initial reaction (eq. 9) that half of the bisacetamide hydrochloride was derived from the adduct **13**. It is not immediately obvious how hydrogen chloride could react with **13** to give acetamide or bisacetamide hydrochloride, and it seemed desirable to examine the reaction of hydrogen chloride with a pure 2-bromo-*N*-bromoacetimidate. Because of its relative stability, the cyclohexene adduct was selected for this work. Titration of an ether solution of **10** at 0° with ethereal hydrogen chloride afforded in 91% yield a crystalline compound, m.p. 157.5–158.5°. This compound has the molecular formula $C_8H_{15}NOBrCl$. Its i.r. spectrum shows strong absorption at 6.0 μ (C=N), a broad peak at 3.5 μ (CH, NH_2^+), and no peak at 3.0 μ (NH). Structure **24** is assigned to this compound. The observation of an orange color during the reaction of **10** with hydrogen chloride is attributed to the formation of BrCl according to eq. 19.

Reaction with Triethylamine

It is known that *N*-bromo compounds react with triethylamine as shown in eq. 20 (8*a*, 16, 17*b*, 46). In agreement with eq. 20, the cyclohexene adduct **10** reacts with triethylamine to give triethylamine hydrobromide, 2-bromocyclohexanone (20%), and, in 75–80% yield, a compound assigned structure **25** on the basis of its i.r. spectrum which was identical with that of the acetimidic acid obtained upon neutralization

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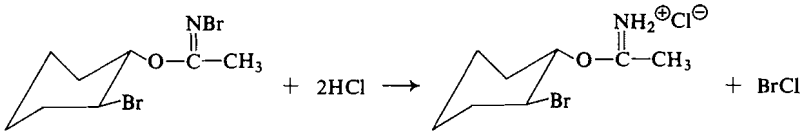
[19] 

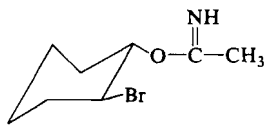
24

[20] $$\text{>NBr} + 2Et_3N \longrightarrow \text{>NH} + Et_3N{\cdot}HBr + Et_2NCH{=}CH_2$$

of **24** ($\lambda_{max}(CHCl_3)$ 3.0, 6.04 μ):

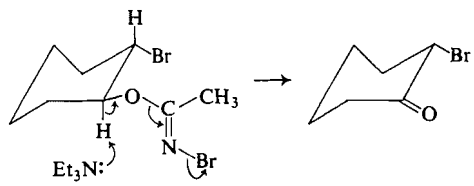
$$\mathbf{10} \xrightarrow{Et_3N} \mathbf{25} \xleftarrow{NaHCO_3} \mathbf{24} \xleftarrow{2HCl} \mathbf{10}$$

Further evidence that the reaction of the cyclohexene adduct with triethylamine occurs mainly at the nitrogen atom is found in the n.m.r. spectrum of the 3,3,6,6-tetradeuterio analog of **25**. Although the methyl peak of this compound shifts from τ 7.62 in the adduct **11** to τ 7.97, the position of the AB quartet for the *trans* tertiary protons is unchanged.



25

Formation of 2-bromocyclohexanone in this reaction is considered to be the result of the elimination shown in eq. 21.

[21] 

+ CH_3CN + $Et_3N{\cdot}HBr$

Formation from 10 of Cyclohexene Bromohydrin and 2-Bromocyclohexanone

If the acetimidic acid **25** is allowed to stand at room temperature, a slow conversion to cyclohexene bromohydrin is observed (*cf.* ref. 47). This observation provides an important clue to the mode of formation of the bromohydrin from the 2-bromo-*N*-bromoacetimidate. It was already noted in the initial experiments that continued refluxing of the mixture obtained from the reaction of cyclohexene with NBA leads to a steady increase in the ratio of cyclohexene bromohydrin to cyclohexene dibromide and that the bromohydrin is not formed at the expense of the dibromide. It has also been noted that refluxing of a 10% solution of pure **10** in carbon tetrachloride causes complete decomposition in one hour. The g.l.c. analysis of the latter mixture revealed a 44:36:20 mixture of **5**, **6**, and **7**. When the solvent was removed and the residue allowed to stand overnight at room temperature, this ratio changed to 22:65:13. Since **25** was not detected by the g.l.c. procedure employed to determine the proportions of the volatile products **5**, **6**, and **7** these results can be interpreted in terms of the sequence shown in eq. 22. The i.r. spectra shown in Fig. 3

[22] $$\mathbf{10} \xrightarrow[80^\circ]{CCl_4} \mathbf{5} + \mathbf{25} + \mathbf{7} + \text{Tar}$$
$$\mathbf{25} \xrightarrow{-CH_3CN} \mathbf{6}$$

support this interpretation. The initial product of decomposition of **10** (lower spectrum) shows a strong absorption at 6.0 μ, assigned to the C=N group of **25**, and a weaker absorption at 5.8 μ, assigned to the carbonyl group of **7**. The upper spectrum is that of the product obtained after the solvent was removed and the residue allowed to stand at room temperature overnight.

If the formation of the bromohydrin from the 2-bromo *N*-bromoacetimidate is to be explained in terms of the sequence,

$$ROC(CH_3){=}NBr \longrightarrow ROC(CH_3){=}NH \longrightarrow ROH$$

it is necessary to provide a hydrogen source for the reaction **10** → **25**. Two possible hydrogen sources can be suggested. The first is HBr (*cf.* eq. 19[2]) formed, together with 2-bromocyclohexanone, by the route suggested below.

[2]During the decomposition of **10** in dimethylformamide, already described, a bromine color developed and then faded, possibly because of reaction or distillation from the medium, or both.

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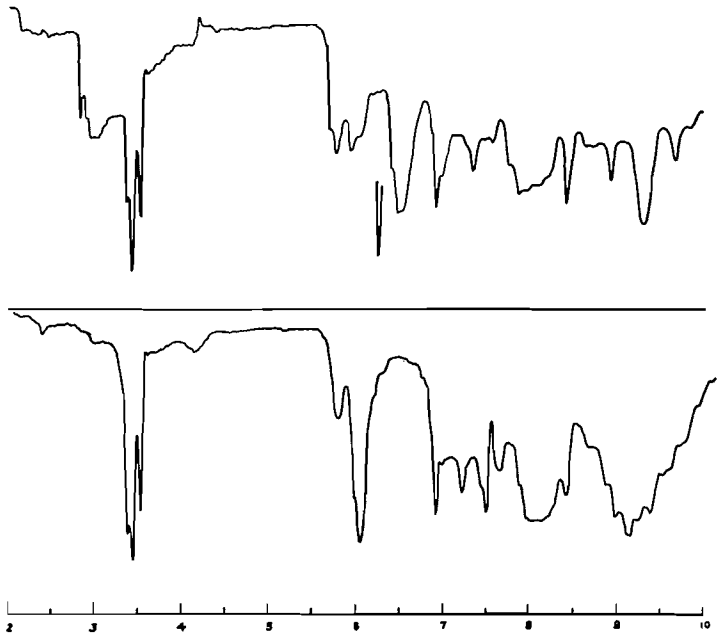
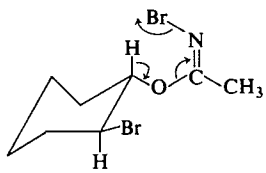


FIG. 3. The i.r. spectrum of the product resulting from thermal decomposition of **10**. The lower spectrum is that obtained when **10** was refluxed in CCl_4 for 1 h. The upper spectrum is that of the product obtained after the solvent was removed and the residue allowed to stand overnight at room temperature.



$\longrightarrow$ 7 + HBr + CH_3CN

This cannot be the sole hydrogen source for this transformation because, in the materials balance, equal amounts of bromohydrin and 2-bromocyclohexanone or derived products would be expected. In fact, the amount of bromohydrin always exceeds that of bromoketone. A second hydrogen source for the reaction **10** $\rightarrow$ **25** is the adduct **10** itself. It has been demonstrated recently (48) that heating of a solution of benzophenone *N*-bromoimine in cyclohexane affords cyclohexyl bromide. Although the mechanism of this bromination was not studied, the reaction does not provide precedent for a process, eq. 23. In the present case,

[23] $R_2C{=}NBr + R'H \rightarrow R_2C{=}NH + R'Br$

reaction of **10** with itself according to eq. 23 would be expected to afford, in addition to **25**, polybrominated adducts and/or the high boiling residues encountered in the decomposition of **10**.

Rearrangement to Aminoacetates

The i.r. spectrum displayed in the upper curve of Fig. 3 shows carbonyl absorption at 5.7 *and* at 5.8 μ. The 5.8 μ peak is attributed to 2-bromocyclohexanone; the 5.7 μ peak is consistent with an ester carbonyl absorption. Since the precursor of this material, with the spectrum shown in the lower curve of Fig. 3, appears to have no peak at 5.7 μ, it can be speculated that the decomposition of **25** leads not only to the bromohydrin but also to acetate-containing material. Attempts to obtain this compound in pure form were not successful, but the apparently analogous product of decomposition of the 1-methylcyclohexene adduct could be isolated in crystalline form, m.p. 208–210°. This compound has the formula $C_9H_8BrN_2O$; its n.m.r. and i.r. spectra, reproduced in Fig. 4, are compatible with structure **26**, 2-acetoxy-2-methylcyclohexylammonium bromide. Cyclization of the imidic acid **27** would afford the oxazoline hydrobromide **28**; hydrolysis of **28** could proceed to give the salt **26** or the acetamido alcohol **29**. A search for **29** was not made.

The scheme shown in eq. 24, if correct, provides chemical support for the structure and

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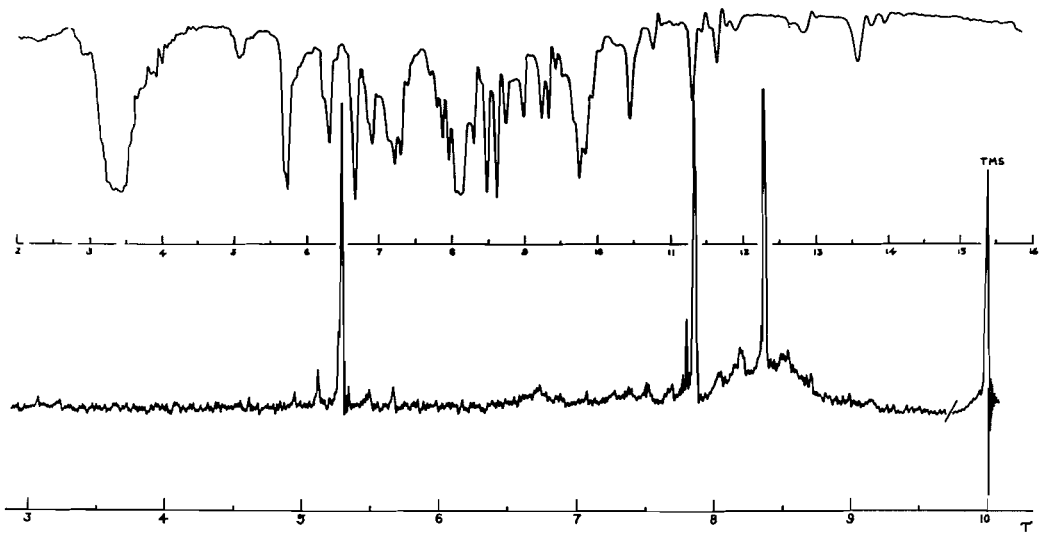
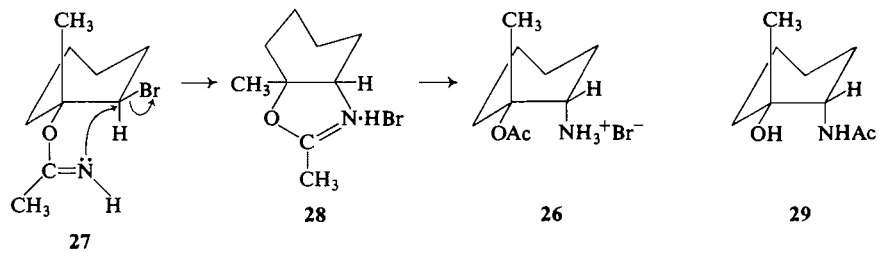


FIG. 4. The i.r. (KBr) and n.m.r. (D_2O) spectra of **26**.

[24]



stereochemistry of the 1-methylcyclohexene adduct **15**. Formation of the oxazoline would require a *trans* relationship of the electronegative substituents; and attack on the C—Br bond with inversion of configuration would not be expected in the case of the tertiary bromide **16**.

Experimental

Melting points were determined on a Fisher–Johns m.p. apparatus, and are uncorrected. Boiling points are also uncorrected. The i.r. spectra were recorded on a Beckman IR 5A instrument unless otherwise indicated. The n.m.r. spectra were obtained on a Varian A60 spectrometer, tetramethylsilane (TMS) being employed as the internal standard, unless otherwise specified. The g.l.c. determinations were performed on a Beckman GC-2 chromatograph; a Fisher Prep. Partitioner was employed for preparative work. The column packing was 15% butanediol succinate on Embacel and separations were conducted at 130°. Microanalyses are by Dr. C. Daesslé, Montreal, Spang Microanalytical Laboratory, Ann Arbor, and J. Booker, Queen's University.

All solvents were Fisher Certified Reagent Grade and were used without further purification except for drying, where indicated, by conventional means.

N-Bromosuccinimide

BDH Reagent Grade material was employed.

N-Bromoacetamide

Commercial NBA was dissolved in boiling benzene, no attempt being made to remove the color of bromine in the solution. Perfectly formed colorless needles, m.p. 108°, were obtained when the solution was allowed to cool undisturbed at room temperature. The precipitated solid was collected, washed to whiteness with 30–60° petroleum ether and allowed to dry in the air. This material could be stored for long periods in the cold without apparent deterioration.

Olefins and Ketones

All substrate olefins and ketones except tetramethylethylene and 1-methylcyclohexene, were commercial products of "Reagent" or equivalent grade and were used unpurified if g.l.c. analysis indicated no significant (<1%) contamination. If color could be detected or g.l.c. analysis indicated significant impurity the material was distilled before use.

Tetramethylethylene

This material, b.p. 70–71° was synthesized by reduction of pinacolone, followed by acid-catalyzed dehydration of the resultant alcohol (49). Integration of the methyl peak at τ 8.36 against all extraneous peaks indicated greater than 90% purity.

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1-Methylcyclohexene

This olefin, b.p. 108–110°, n_D^{25}, 1.4475, lit. (50) n_D^{25}, 1.4478, was prepared by acid-catalyzed dehydration of 1-methylcyclohexanol. Integration of the n.m.r. spectrum showed that the downfield multiplet centered at τ 4.66 was in the ratio 1:11 with the remaining upfield signals.

2-Bromocyclohexanone

Cyclohexanone was brominated with NBS (51) to yield 2-bromocyclohexanone, b.p. 82–84°/6 mm, lit. (52) 74°/3 mm.

3-Bromocyclohexene

This compound was prepared by treatment of cyclohexene with NBS (16) and had b.p. 60–62°/14 mm, lit. (8*a*) 55–57°/11 mm.

1,2-Dibromocyclohexane

A solution of molecular bromine in chloroform was added dropwise to a magnetically stirred solution of an equimolar amount of cyclohexene in chloroform maintained at 0–5°. Evaporation of the solvent and distillation gave a product b.p. 92–94°/10 mm, lit. (20) 93–96°/10 mm.

1,2-Dibromocyclopentane

The compound had b.p. 67–68°/11 mm, lit. (53) 75°/17 mm.

α,β-*Dibromostyrene*

This compound, m.p. 72–73°, lit. (38) 73–74°, and *trans*-α,α′-*dibromostilbene*, m.p. 225–228°, lit. (38) 235–237° were synthesized in the same manner as was 1,2-dibromocyclohexane.

Cyclohexene Bromohydrin

This compound, b.p. 85–87°/10 mm, lit. (54) 86.6–88.4°/10 mm, was prepared by ring opening of cyclohexene oxide with gaseous hydrogen bromide (55).

1-Methylcyclohexene Bromohydrin

This compound, b.p. 98–101°/10 mm, lit. (50*b*) 96.8°/8.5 mm, and *styrene bromohydrin* b.p. 134–136°/10 mm, lit. (56) 120–123°/5 mm, were synthesized by the method of Guss and Rosenthal (56) by reaction of the respective olefins with NBS and water.

The purity of all reference compounds, except α,α′-dibromostilbene and the styrene derivatives, was established by g.l.c. examination. The identity of the styrene derivatives was confirmed by determination of their n.m.r. spectra described later.

*2-Bromocyclohexyl-N-bromoacetimidate (**10**)*

A solution of cyclohexene (41.0 g, 0.5 mol) in carbon tetrachloride (100 ml) was added rapidly to a refluxing suspension of NBA (69.0 g, 0.5 mol) in carbon tetrachloride (400 ml) in a 1 l three-necked flask.[3] Refluxing was maintained by the heat from a 100 W Photoflood No. 2 lamp with reflector mounted close to the reaction flask. The reaction soon became vigorous and, after approximately 5 min, the solid NBA had disappeared and yellow droplets of acetamide could be discerned adhering to the sides of the vessel. The otherwise colorless reaction mixture was immediately cooled in an ice-bath until crystallization of the acetamide[4] was complete and this solid was then collected (15.4 g, 104% based on eq. 9). The mother liquor was distilled under reduced pressure below 40 °C to a residue of 81.1 g; the distillate was then found to contain 16.1 g (80%, based on eq. 9) of cyclohexene by titration of an aliquot with a standardized solution of bromine in carbon tetrachloride.

The residue, diluted with 30–60° *petroleum* ether (10 ml) and stored overnight at −20°, afforded 0.7 g (1%) of *trans*-2-acetamidocyclohexyl bromide, m.p. 110–111°, lit. (57) 109–110°. The i.r. spectrum of this product shows amide absorption at 6.05 and 6.38 μ, and the n.m.r. spectrum shows a peak at τ 7.93 consistent with the presence of an acetamidyl methyl group.

The filtrate was concentrated, *ethyl* ether (10 ml) was added and this solution was kept overnight at −20°. The massive camphor-like crystals then obtained weighed 26.4 g (36%) and melted at 28.0–28.5°.

Anal. Calcd. for $C_8H_{13}NOBr_2$: C, 32.12; H, 4.38; N, 4.72; Br, 53.46. Found: C, 32.34; H, 4.25; N, 4.69; Br. 53.57.

No attempt was made to optimize the recovery of crystalline **10**; however, it was noted that the i.r. spectrum of the residue following removal of **10** was superimposable upon that of the crystalline material.

*Reaction of NBA with Tetramethylethylene. Preparation of **12***

(i) In Carbon Tetrachloride

Tetramethylethylene (4.6 g, 0.055 mol) was added rapidly to a refluxing suspension of NBA (7.8 g, 0.059 mol) in carbon tetrachloride (25 ml), heat being supplied by a 100 W Photoflood No. 2 lamp mounted beneath the flask. When the crystalline NBA had disappeared and yellow droplets of acetamide could be seen, the reaction flask was immediately cooled in an ice–bath and the precipitated acetamide (1.3 g, 78%) was collected. The filtrate was evaporated to yield 5.7 g (66%) of a faintly yellow oil which was diluted with a small amount of ether and stored at −20°. The product crystallized overnight to a solid mass from which well-formed needles (4.7 g, m.p. 40–41°) were obtained; these crystals were washed with a small quantitiy of ice-cold anhydrous ether and analyzed.

Anal. Calcd. for $C_8H_{15}NOBr_2$: C, 31.90; H, 4.98. Found: C, 31.70; H, 4.97.

(ii) In Ether[5]

To a suspension of NBA (1.68 g, 0.013 mol) in anhydrous ether (10 ml), magnetically stirred and cooled in an ice-bath, was added dropwise a solution of tetramethylethylene (1.0 g, 0.012 mol) in anhydrous ether (5 ml). No apparent reaction had taken place by the end of the addition. A crystal of the solid residing at the bottom of the reaction flask was, therefore, extracted and its m.p. determined (107–108°); a mixture m.p. of this material with an authentic sample of NBA was 107–108°.

[3]Care should be taken to use a reaction flask of capacity at least twice the volume of solvent in order to obviate the possibility of overflow of its contents when the highly exothermic reaction begins.

[4]In all cases acetamide was identified by determination of its m.p. and a mixture m.p. with an authentic sample.

[5]Wohl (1) mixed 10 g of tetramethylethylene in 36 ml of ether with 16 g of NBA "under good cooling" and allowed the reaction to go to completion overnight. No other details, including the method of work-up, were mentioned.

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No further change was apparent after the reaction mixture had been stored overnight at 0° in the dark.

After approximately 4½ h stirring at room temperature in the diffuse light of the laboratory, the needles of NBA could not be detected and a voluminous precipitate was dispersed throughout the reaction medium. Filtration yielded acetamide (0.43 g, 78%, m.p. 76–78°; mixture m.p. with acetamide 76–78°). Evaporation of the filtrate yielded 1.5 g (75%) of a colorless oil, whose i.r. spectrum was almost identical with that of the crystalline adduct **12** prepared in (*i*), and which could be crystallized to give material melting at 39–40° by seeding with the former product.

Reaction of NBA with Styrene. Preparation of ***13***

A solution of styrene (1.0 g, 0.01 mol) in carbon tetrachloride (10 ml) was added rapidly to a refluxing suspension of NBS (2.76 g, 0.02 mol) in carbon tetrachloride (50 ml), with irradiation by a 100 W Photoflood No. 2 lamp. As soon as the NBA had disappeared, the mixture was rapidly cooled in an ice-bath, the precipitated acetamide was collected (0.4 g, 68%) and the filtrate was concentrated under reduced pressure at room temperature. The i.r. spectrum of the residue (2.7 g, 80%) showed the characteristic adduct absorptions at 6.2 and 7.8 μ and, as well, some slight absorption at 5.8 and 5.95 μ. The product was dissolved in ether (20 ml) and stored at −20° for 60 h. Fine needles (0.8 g, m.p. 72–73°) separated out and were identified as α,β-dibromostyrene by a mixture m.p. with an authentic sample (72–74°) and by superimposition of the i.r. spectra of the two samples.

The adduct has not yet been crystallized; that this may be due to its instability is evident upon examination of the n.m.r. spectrum of the newly formed product of the NBA–styrene reaction as a function of time. Immediately after isolation this spectrum showed, in addition to unreacted styrene, a triplet (1H) centered at τ 4.15, a doublet (2H) centered at 6.57, and a sharp peak (3H) at 7.85. Within 1 h at room temperature, the peaks at τ 4.15, 6.57, and 7.85 disappeared completely; (in the i.r. spectrum the characteristic peaks at 6.2 and 7.8 μ also disappeared). A doublet, centered at τ 6.18, was now present and was attributed to the β-protons of α,β-dibromostyrene. In the n.m.r. spectrum of the latter compound the α- and β-protons are found, respectively, at τ 4.95 and 6.18; however, in the n.m.r. spectrum of the concentrated NBA–styrene product the signal at 4.95 is obscured by signals due to residual styrene. This proton was readily seen when the product of decomposition was exhaustively evaporated to remove the residual styrene.

Reaction of NBA with 1-Methylcyclohexene. Preparation of ***15***

1-Methylcyclohexene (0.96 g, 0.01 mol) was added rapidly to a refluxing suspension of NBA (1.38 g, 0.01 mol) in carbon tetrachloride (25 ml) with irradiation from a 100 W Photoflood No. 2 lamp. Work-up in the usual manner yielded 1.4 g (81%) of a colorless oil whose i.r. spectrum, shown in Fig. 2, has the characteristic peaks at 6.22 and 7.86 μ. Dilution with ether and storage at −20° failed to crystallize the adduct.

The n.m.r. spectrum of the colorless oil, immediately after isolation, showed, in addition to the two methyl peaks and the ring protons, a 1-proton quartet centered at τ 5.1. After 15 min this quartet had disappeared and a triplet centered at τ 5.4, and a multiplet centered at 5.9 were present. The proton geminal to bromine in 1,2-dibromo-1-methylcyclohexane appears as a triplet centered at τ 5.4. 1-Methylcyclohexene bromohydrin shows complex absorption centered at τ 5.9.

Variable quantities of a chloroform and carbon tetrachloride - insoluble white solid, m.p. 208–210°, were isolated following decomposition of the adduct **15** in these solvents. This solid, a crystalline compound soluble in water, was isolated by filtration, washing with ether, and air-drying. Its i.r. and n.m.r. spectra, shown in Fig. 4, are compatible with structure **26**.

Anal. Calcd. for $C_9H_8BrN_2O$: C, 42.8; H, 7.14. Found: C, 42.89, 43.15; H, 7.53, 7.62.

Reaction of NBA with trans-Stilbene

trans-Stilbene (4.5 g, 0.025 mol) was dissolved in carbon tetrachloride (300 ml) and to the magnetically-stirred solution was added NBA (6.9 g, 0.050 mol). The reaction flask was immersed in a cold water bath which was also magnetically stirred. The temperature of the water bath was slowly raised by irradiation with a 100 W Photoflood No. 2 lamp mounted close to it. No apparent reaction took place until the bath temperature reached 60°, at which point the rate of solution of NBA seemed to increase dramatically; before all of the NBA had dissolved, the reaction mixture became noticeably yellow. The irradiation was immediately halted and the reaction mixture was quickly cooled in an ice-bath. The carbon tetrachloride - insoluble material was collected and triturated with cold water. After drying, the water-insoluble residue weighed 3.2 g and had an i.r. spectrum, m.p., and mixture m.p. identical with those of an authentic sample of α,α′-dibromostilbene.

The i.r. spectrum of the carbon tetrachloride filtrate showed no trace of a bromoacetimidate. Removal of the solvent yielded 4.2 g of an intractable brownish semi-solid residue.

Thermal Decomposition of 2-Bromocyclohexyl-N-bromoacetimidate

(i) In Carbon Tetrachloride and Cyclopentene

The crystalline adduct **10** (1 g) was dissolved in carbon tetrachloride (10 ml) and the solution quickly brought to reflux on a steam bath. One milliliter aliquots of the refluxing solution were withdrawn at 15–20 min intervals and subjected to i.r. and g.l.c. analysis. The g.l.c. analysis indicated formation of three compounds. These compounds were isolated by preparative g.l.c. and shown to be (in order of increasing retention time) cyclohexene dibromide, cyclohexene bromohydrin, and 2-bromocyclohexanone. The identifications were made in each case by i.r. and g.l.c. analysis.

When cyclopentene was employed as the solvent, g.l.c. analysis readily revealed cyclohexene dibromide, but no trace of cyclopentene dibromide could be detected.

(ii) In Dimethylformamide

The crystalline adduct **10** (1 g) was dissolved in DMF (5 ml), and the solution was heated on the steam bath for 1 h. The product was then diluted with water, extracted with ether, and the ether extract dried over anhydrous sodium sulfate and evaporated. The composition

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of the residue was established, as in (*i*) by i.r. and g.l.c. analyses.

This experiment was repeated in the presence of added lithium chloride (0.1 g, a molar equivalent) in order to test the effect of added chloride ions on the nature of the decomposition in DMF. There was no effect.

(iii) In a Closed System

The crystalline adduct **10** (0.6 g, 0.002 mol) was sealed in a pyrex tube and rapidly heated on the steam bath. The melt soon darkened and an eruption of vapor followed closely. When the reaction tube was cooled, a clear light brown oil was noted over a dark brown semi-solid residue. The tube was opened and the oil washed out with carbon tetrachloride. Evaporation of the solvent and distillation of the residue afforded 1,2-dibromocyclohexane (0.14 g, 30%) identified by comparison of its g.l.c. retention time and its i.r. spectrum with those of an authentic sample. The intractable semi-solid residue weighed 0.43 g.

*Preparation of 2-Bromocyclohexylacetimidium Chloride (**24**)*

Crystalline **10** (0.60 g, 0.002 mol) was dissolved in 10 ml of anhydrous ether. The solution was cooled to 0°, stirred, and treated dropwise with 45 ml of 0.07 *N* ethereal hydrogen chloride. In the course of the addition the reaction mixture acquired a decidedly orange tint and a white crystalline solid separated out. The mixture was stirred for 2 h in the ice-bath after the addition was complete and the solid was then collected. It weighed 0.34 g and melted at 154–155°. Concentration of the orange-colored filtrate caused loss of the orange color and precipitation of a further 0.15 g of the white solid, m.p. 152–155°. The total yield of the crystalline solid corresponded to 91% conversion of the bromoimidate to its derived salt on the basis of the hydrogen chloride utilized. Recrystallization from methanol–ether gave fine needles, m.p. 157.5–158.5° (sealed tube).

Anal. Calcd. for $C_8H_{15}NOBrCl$: C, 37.42; H, 5.85. Found: C, 37.26; H, 5.63.

*Neutralization of **24**. Preparation of 2-Bromocyclohexylacetimidic Acid (**25**)*

An ether suspension of the salt **24** was shaken with 1% aqueous bicarbonate. The ether layer was then separated, dried, freed of solvent, and the i.r. spectrum of the residue determined. Strong absorption at 6.0 μ was still present but the C–H region of the spectrum was now cleanly resolved and a sharp peak was observed at 3.0 μ. When an ether solution of this product (**25**) was shaken with D_2O, dried over anhydrous sodium sulfate, and the solvent removed, the i.r. spectrum of the residue showed no absorption at 3.0 μ. Instead a sharp peak was present at 4.1 μ indicating an N–H to N–D transformation. There was no change in the remainder of the spectrum.[6]

*Reaction of **10** with Triethylamine*

To an ice-cooled stirred solution of **10** (6.0 g, 0.02 mol) in anhydrous ether (20 ml), was added dropwise a solution of triethylamine (2.0 g, 0.02 mol) in anhydrous ether (20 ml). After the addition was complete, the product was stored in the refrigerator for 2 h and the precipitated solid was then collected (3.2 g) and identified as triethylamine hydrobromide on the basis of its i.r. spectrum and a mixture m.p. The filtrate was washed with cold water, dried over anhydrous sodium sulfate, and evaporated to yield 4.2 g of a light brown oil. The i.r. spectrum of this oil was found to contain all of the peaks of **25**, as well as absorption at 5.8 μ attributed to the carbonyl stretching band of 2-bromocyclohexanone. The presence of the latter compound was confirmed by g.l.c. comparison with an authentic sample of the bromoketone using a column of 1% SE 30 on Embacel in addition to the butanediol succinate column.

The n.m.r. spectrum of the product of triethylamine treatment of the adduct **11** from cyclohexene-3,3,6,6-d_4 is almost identical with that of the precursor adduct except for an upfield shift of the methyl peak to τ 7.97. The hydrogen atoms corresponding to H_A and H_B of the original adduct remain as a typical AB quartet with $J = 9$ Hz.

Decomposition of NBA

The NBA (6 g, 0.043 mol) was dissolved in refluxing carbon tetrachloride (500 ml) and the solution irradiated with an ordinary 200 W bulb.[7] Bromine was slowly codistilled with carbon tetrachloride as it formed, and collected in an ice-cooled receiver. After approximately 5 h, the residual solution was only faintly yellow. At this point crystals of a colorless solid were present in the water-cooled condenser; these were washed out with anhydrous ether and collected (0.2 g, m.p. 76–77°). The residual solution was then concentrated under reduced pressure below 40° and the residue triturated with ether to give a further 0.5 g of crystals, m.p. 76–78°. The volume of the bromine-containing distillate was then accurately measured, a sample retained for titration, and the remainder evaporated to dryness and the residue triturated with ether to yield a third crop of colorless crystals (0.2 g, m.p. 76–78°). The crystals were identified as acetamide by a mixture m.p. determination with an authentic sample (total yield, 0.9 g, 35% based on NBA; 70% based on eq. 10).

Titration of the bromine-containing aliquot with a standardized solution of cyclohexene in carbon tetrachloride indicated that the distillate contained 0.018 mol of Br_2, corresponding to 84% of that expected from the stoichiometry shown in eq. 10.

Methyl isocyanate and diacetylhydrazine (anticipated from coupling of two acetamidyl radicals) were, however, not detected.

Preparation of N,N-Dibromoacetamide (NDBA)

An ice-cooled solution of potassium hydroxide (112 g, 2.0 mol) in 1 l of water was added dropwise to a well-stirred mixture of acetamide (59 g, 1 mol) and bromine

[6]We thank Dr. H F. Shurvell for suggesting this procedure.

[7]The use of stronger illumination, such as the 100 W Photoflood No. 2 lamp used in bromoacetimidate preparations, led to more complex products; *bis*-acetamide hydrobromide m.p. 131°, lit. (32) 131° was isolated from such a decomposition. Buckles *et al.* (32) have reported deposition of impure *bis*-acetamide hydrobromide from a u.v. irradiated solution of NBA in chloroform.

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(320 g, 2.0 mol), the temperature of the reaction mixture being maintained between 0 and 5° by cooling in an ice-salt bath. After the addition was complete the orange colored solid (obviously impregnated with bromine) was rapidly filtered and washed with ice-cold water. The wet bright orange solid was vacuum dried to yield 60.8 g (30%) of a bright yellow solid. This material could be recrystallized with care from hot water to give a 52% recovery of lustrous golden yellow plates, m.p. 100°, lit. (34) 100°.

Anal. Calcd. for $C_2H_3NOBr_2$: C, 11.06; H, 1.38. Found: C, 11.03; H, 1.55.

Reaction of NDBA with Cyclohexene

Cyclohexene (0.82 g, 0.01 mol) in methylene chloride (10 ml) was added dropwise to a magnetically-stirred solution of NDBA (2.17 g, 0.01 mol) in methylene chloride (20 ml), the reaction mixture being cooled in an ice-bath. At the end of the addition the solution was decidedly yellow. Evaporation of the solvent yielded 2.82 g of a yellow oil whose i.r. spectrum showed the absorptions at 6.2 and 7.85 μ characteristic of the bromoacetimidate adduct **10**, as well as a peak of much lower intensity at 5.9 μ. The oil was diluted with ether, and petroleum ether (30–60°) was added to the cloud point. Storage at 0° produced colorless needles, 50 mg, of **8**, m.p. 111–112° (yield 2.5%). The mother liquor was evaporated to dryness and the residue treated with ether (1 ml). After 1 day at −20° crystallization had occurred. The crystals were collected and identified as **10** by m.p. and i.r. determinations.

Competition Experiment of NDBA with Cyclohexene and Styrene

The above experiment was repeated except that a mixture of cyclohexene (0.01 mol) and styrene (1.04 g, 0.01 mol) was added to the NDBA solution. The n.m.r. spectrum of the resulting product showed the peaks of **10** and of styrene. Peaks corresponding to the adduct **13** and styrene dibromide were not observed.

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