Bromination of Norbornene: the Question of Bromonium Ions vs. 6,1-Hydride Shift

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Received October 1, 1970

The reaction of norbornene (1) with bromine has been re-investigated and found to give in addition to bromonortricyclene (2) and 2-exo-bromonorbornane (20) a complex mixture of dibromides of which five (15-19) have been isolated and identified. These dibromides have been found to be kinetically controlled products of ionic addition. Apparently dibromide 15 is also formed to some extent in carbon tetrachloride by a radical mechanism. The product composition from the bromine addition has been compared with that of the analogous chlorination and bromofluorination reactions. Degradation of the 2-exo,3-endo-dibromonorbornane from bromination of $5,6^{-14}$ C-norbornene has shown that this dibromide is formed by two ionic routes: (a) from a bromonium ion 14 (or its equivalent), and (b) from the cation 12 formed degradation method.

La réaction du norbornène (1) avec le brome a été réexaminée et s'est avérée donner, en plus du bromonortricyclène (2) et de l'exo bromo-2 norbornane (20), un mélange complexe de composés dibromés dont cinq (15-19) ont été isolés et identifiés. Il a été montré que ces composés dibromés sont des produits cinétiquement contrôlés résultant d'une addition ionique. Il semble que le dibromo 15 se forme également de façon appréciable dans le tétrachlorure de carbone par un mécanisme radicalaire. La composition des produits de la réaction d'addition du brome a été comparée aux réactions analogues de chloration et de bromofluoration. Par dégradation du dibromo exo-2, endo-3 norbornane obtenu par bromation du ¹⁴C-norbornène-5,6, il a été montré que ce dibromure est formé par deux voies ioniques: (a) à partir d'un ion bromonium 14 (ou ses équivalents), et (b) à partir du cation 12 formé par une migration-1,6 d'hydrure. Des améliorations ont été apportées à la première et dernière étapes de la méthode standard de dégradation du norbornène.

Canadian Journal of Chemistry, 49, 885 (1971)

Introduction

In the course of a study of the reaction of "bromine fluoride" (N-bromoacetamide + hydrogen fluoride) with norbornene (1), it was found that the major dihalo products were 7syn-bromo-2-exo-fluoronorbornane (3) and 7anti-bromo-2-exo-fluoronorbornane (4), (Scheme 1) (1, 2). Since the ionic reaction of either "bromine fluoride" or bromine with norbornene would presumably lead to the same first intermediate, the 7-anti-isomer 4 was unexpected on the basis of the reported bromination of norbornene (3-5), from which the only dibromo products identified were 7-syn,2-exo-dibromonorbornane (19) and 2-exo,3-endo-dibromonorbornane (15). Most of the earlier investigation of this bromination reaction was done before g.l.p.c. and n.m.r. spectroscopy were available, and although some of the conclusions reached earlier (3, 4) have since been revised (5) (the bromination product was found to contain other dibromides), no further report has been published. To clarify the situation a re-investigation of the bromination reaction was undertaken. After the present work was undertaken, three other studies of halogenation of norbornene were reported which further underlined the desirability of reconciling the various reaction products. In one case (6) N,N-dibromobenzenesulfonamide was the halogenating agent, and the products **2**, **5**, and **6** were analogous to those from the "bromine fluoride" reaction, while in the other studies describing the chlorination of norbornene (7, 8), three of the four products, **7–10**, of the ionic reaction were analogous to the compounds reported from the bromination (Scheme 1).

Structural and Stereochemical Assignment of the Dibromides

When the bromination of norbornene in carbon tetrachloride at 0° was repeated according to the directions of Kwart and Kaplan (3, 4) and

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the crude product was examined by g.l.p.c.,¹ there were present eight peaks with retention times expected for dibromonorbornanes (Fig. 1). Five of these peaks corresponded to compounds present in greater than 1% yield, and they were isolated by preparative g.l.p.c.¹ From the clean n.m.r. spectra (Fig. 2) of four of the five g.l.p.c. fractions there is no reason to suspect the presence of more than one compound per peak. The five dibromonorbornanes² were assigned struc-

²There appears to be no reason to doubt that all five compounds have the norbornane skeleton. For two of the isomers this has been proved: **19** has been reduced to norbornane by sodium and *t*-butyl alcohol, and **15** has been degraded to *cis*-1,3-cyclopentane dicarboxylic acid. Moreover, **19** is readily isomerized to the other four dibromides by hydrogen bromide, and the bicyclo[2.2.1] system would not be expected to be equilibrated with a more strained, less stable bicyclo[3.2.0], [3.1.1], or [4.1.0] system. For example, the bicyclo[3.2.0] system rearranges to the bicyclo[2.2.1] skeleton (9). The n.m.r. spectra exclude the presence of methyl groups and olefinic hydrogens. ture and stereochemistry on the basis of their n.m.r. spectra (including double irradiation spectra), dipole moments, g.l.p.c. retention times, and stability relationships.

Integration of the n.m.r. spectrum of each dibromide shows that every bromine atom is on a carbon atom bearing a hydrogen atom, thereby restricting the number of possible structures to 13 (Table 1). The three 2,3-dibromides have been synthesized previously and their stereochemistry determined unambiguously (10, 11). The *exocis*-2,3- and *endo-cis*-2,3-isomers were not identical with any of the five bromination products isolated. However, the first eluted (g.l.p.c.) di-



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¹When g.l.p.c. equipment with metal columns (copper or stainless steel) and a metal injection block was used, the dibromides were partially decomposed. For this reason a gas chromatograph with a glass column and injection chamber was used both for analytical and preparative g.l.p.c. For preparative work a stainless steel splitter was attached to the exit of the glass column, but little or no decomposition occurred during the short contact time in the metal splitter as tested by re-injection of the eluate. ²There appears to be no reason to doubt that all five

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Increasing retention time FIG. 1. The g.l.p.c. chart of the norbornene bromination product.

bromide was identical with 2-exo, 3-endo-dibromonorbornane (15), one of the two compounds identified by Kwart and Nyce (5). The n.m.r. spectrum (Fig. 2a) is in agreement with that reported (10). Double irradiation of exo H-3 at 4.42 p.p.m. caused the three line pattern from endo H-2 at 3.83 p.p.m. to collapse to a doublet $(J_{endo}H_2-anti H-7 \sim 3 Hz)$, and double irradiation of the bridgehead H-1 and -4 peaks at 2.46 p.p.m. caused the exo H-3 signal to collapse to a doublet $(J_{endo}H_2 - exo H-3 \sim 2.9 Hz)$ while the endo H-2 signal at 3.83 p.p.m. was undisturbed.^{3,4} Therefore the two low field protons are on adjacent carbon atoms. Also in agreement with a vicinal structure is the fact that this dibromide is the most easily dehydrobrominated of the five. The final proof of structure was the degradation of this isomer to cis-1,3-cyclopentane dicarboxylic acid (5) (see below).

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The second dibromide to be eluted (g.l.p.c.) was assigned the 7-anti,2-exo dibromo structure 16. In its n.m.r. spectrum (Fig. 2b) the narrow absorption at 4.43 p.p.m. $(w_{1/2} \sim 4 \text{ Hz})$ is characteristic of a proton on C-7 bearing bromine. (2). The position and three line pattern of the peak at 3.93 p.p.m. is typical of a 2-endo proton on a carbon atom bearing bromine and coupled to the adjacent methylene group. The absence of additional observable splitting from long range

coupling with an anti H-7 suggests that the C-7 bromine occupies this position. The anti orientation of the C-7 bromine atom is confirmed by the dipole moment of 2.4 D (calcd. (12): 2.07 D), a value much too small for the syn-isomer (calcd. (12): 3.92 D) which has been found to be the fifth dibromide. As expected for 16, double irradiation of the bridgehead H-1 (2.56 p.p.m.) had no apparent effect on the endo H-2 peaks but caused H-7 to collapse to a doublet $(J_{H-7}-endo$ H-6 < 1 Hz).³

The fourth dibromide eluted (g.l.p.c.) was crystalline, m.p. 94-95.5°, which property together with very simple i.r. and n.m.r. spectra (Fig. 2d) indicated the presence of a high degree of symmetry in the molecule. Both CHBr protons absorb at the same place (3.77 p.p.m.) with the same pattern and are therefore in identical environments. Of the six possible structures, i and ii have already been excluded. Of the remaining four isomers only 18 and iv have endo protons on carbon bearing bromine as required by the fact that double irradiation of both bridgehead methine hydrogens (2.55 p.p.m.) had no effect on the CHBr pattern. Moreover, double irradiation of the methylene protons (2.08 p.p.m.) caused the CHBr pattern to collapse to a singlet.³ Structure 18 is preferred to iv since both bridgehead methine protons are in identical environments. The low value (0.66 D) of the observed dipole moment is also consistent with structure 18 which would have the lowest moment of any of the 13 isomers (Table 1).

The last dibromide to be eluted (g.l.p.c.) had

³For further details and double irradiation spectra see

⁴LeBel and co-workers (10, 11) have proved the stereostructure of **15** by double irradiation measurements on 2-exo,3-endo-dibromonorborn-5-ene which on hydrogenation gives 15.





FIG. 2. The n.m.r. spectra of dibromonorbornanes in CCl₄ solution at 60 MHz.

an i.r. spectrum identical with that of the 7-syn-2-exo-dibromonorbornane isolated by Kwart and Kaplan (3, 4) and converted by them into norbornane-7-carboxylic acid. The dipole moment of this dibromo isomer (3.30 D) excludes all but five of the possible stereoisomers **19**, **i**, **ii**, iii, and v (see Table 1 for calculated dipole moments), and of these five, the four having both CHBr groups in identical environments can be excluded to leave only 19. The two -CHBr protons of this isomer are clearly different in the n.m.r. spectrum (Fig. 2e) although they overlap.

 TABLE 1. Permissible dibromonorbornanes and their calculated dipole moments



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The chemical shift (~3.90 p.p.m.) is that expected for an *endo* CHBr proton on which is superimposed the "broadened singlet" of C₇HBr proton (3.93 p.p.m.). Comparison with the CHBr n.m.r. region of the 7-*anti*-bromo isomer **16** (Fig. 2b) clearly shows that the 2-*endo*-proton of the last eluted dibromide has an additional long range coupling (*endo* H-2-*anti* H-7) which is missing in the 7-*anti*-bromo isomer **16** which has no 7-*anti* proton.³ Additional chemical evidence for assigning the 7-*syn*-2-*exo* stereochemistry to this isomer is its facile isomerization to a mixture of the other four dibromides upon treatment with hydrogen bromide. The instability of this isomer relative to the others is explicable in terms of repulsive non-bonded interaction between the two bromine atoms which is diminished or absent in the other four isomers found.

The third dibromide eluted has not been assigned a unique structure on spectroscopic grounds alone; however, the number of possible structures may be limited to two, and a choice made on the basis of mechanistic arguments. The n.m.r. spectrum (Fig. 2c) reveals that the two CHBr protons are not in the same environment, nor is either CHBr proton on C-7 since the characteristic narrow peak is not present. Therefore only **17** and **vi** remain as possibilities.



Structure vi would arise from a more circuitous path than 17, and moreover a path requiring a 3,2-hydride shift. There is abundant evidence that 3,2-hydride shift in norbornyl cations is much slower than 6,1- and 6,2-hydride shift and becomes appreciable only under equilibrating conditions (13). However, the bromination reaction is kinetically controlled (see below), and furthermore no other products attributable to 3,2hydride shift were found unless the three very minor unidentified components (Fig. 1) arise in this way. For these reasons structure 17 is assigned to the third dibromide.³

Results and Discussion

Fortunately, it was possible to show that the products of bromination of norbornene at 0° in carbon tetrachloride are those of the kinetically controlled addition reaction. Both bromonor-tricyclene (2) and dibromide 19 can react with hydrogen bromide to give a mixture of the five dibromides, but *under the conditions of the addition* these reactions are undetectable.⁵ In control experiments in the present work it was found that treatment of bromonortricyclene (2) or

 $^{{}^{5}}$ Kwart and Kaplan (3) reported that bromonortricyclene reacts with anhydrous hydrogen bromide at 0° in carbon tetrachloride. However, in their reaction, hydrogen bromide was passed through the solution for 12 h, much more drastic treatment than in the addition reaction which was worked-up after 5–20 min and in which the hydrogen bromide concentration was much lower.



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dibromide 19 at 0° in methylene chloride (in which hydrogen bromide is more soluble than in carbon tetrachloride) with more than 1 mol equiv of anhydrous hydrogen bromide gave no reaction over periods longer than the time required for bromine addition to norbornene (see Experimental).⁶ The other four dibromides were also shown to be inert to hydrogen bromide under the addition reaction conditions. Brominations of norbornene carried out in the presence of suspended powdered calcium carbonate gave the same proportional yields of the five dibromides as were obtained in the absence of calcium carbonate within experimental error, although the yield of 2-exo-bromonorbornane was drastically reduced with a corresponding increase in 2 (Table 2). In bromination reactions in which the crude product was not washed to remove hydrogen bromide, the product composition was insensitive to the time that elapsed between reaction and g.l.p.c. analysis. Therefore, the dibromide isomers found are kinetically controlled addition products and do not result from secondary reactions or isomerizations.⁷

In view of Kwart and Kaplan's earlier suggestion that a radical chain reaction might be involved in the formation of one of the dibromides, and since Poutsma's recent work (7) revealed both ionic and free radical components in the chlorination of norbornene in carbon tetrachloride solution, it was necessary to establish the nature of the processes involved in the bromination reaction. The choice of solvent is apparently critical. The bromination in methylene chloride was found to be insensitive to concentration differences and to the radical scavenger oxygen (Tables 2 and 3). If some of the dibromides had been partially or wholly formed by radical processes, a change in product ratios

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would have been expected, but within experimental variation none was observed. In carbon tetrachloride on the other hand, although the dibromide distribution did not change in the presence of oxygen (7), the amount of 2-exo,3endo dibromide 15 increased with increasing concentration of norbornene or bromine while the amount of 2-exo,7-syn dibromide 19 decreased. Furthermore, when a radical, diphenylpicrylhydrazyl, was present in the bromination of high concentrations of norbornene in carbon tetrachloride, the amount of 15 was reduced by half compared to bromination in the absence of the radical, and the dibromide distribution was essentially that obtained in methylene chloride solution. This evidence points to a radical component leading mainly to 15 in the formation of dibromonorbornanes in carbon tetrachloride; if radical intermediates are formed in methylene chloride, they are apparently scavenged by the solvent before they can give rise to dibromonorbornanes.8

A mechanistic interpretation of the *ionically* formed products and product ratios can now be made. The origin of the five dibromonorbornane isomers is consistent with *exo*-addition of a cationic bromine species to norbornene followed by 6,1- or 6,2-hydride shift in the resulting non-classical ion (or Wagner-Meerwein related classical cations **21**) and reaction with bromine or bromide ion. The three non-classical ions, **11**, **12**, and **13**, can give rise to three pairs of dibromides (Fig. 3) of which the only one not formed was the

⁶Actually, the maximum amount of hydrogen bromide that would have been present at 0° was much less than 0.2-0.36 of the molar amount of norbornene used since some of the hydrogen bromide produced in the formation of bromonortricyclene then reacted with norbornene to give 2-exo-bromonorbornane (20). This latter reaction was fast since the amounts of 2 and 20 were always approximately equal.

⁷The formal possibility that some or all of these kinetically controlled products might have arisen from initially formed *exo-cis*-2,3-dibromonorbornane (i) in a fast reaction is excluded both by LeBel's finding (10) that i is a major product of the radical addition of hydrogen bromide to 2-bromonorbornene, and also by our finding that i is unchanged by hydrogen bromide in methylene chloride at 0° .

⁸The unlikely possibility that all of the dibromides are being formed by free radical mechanisms in carbon tetrachloride can be excluded by two observations. Firstly, addition of diphenylpicrylhydrazyl changed the dis-tribution of dibromonorbornanes contrary to what would be expected for an all radical path. Secondly, the bromination of a mixture of norbornene and toluene gave less than 0.5% of benzyl bromide. From bond dissociation energies (14) the addition of a bromine atom to a double bond is approximately thermally neutral. How-ever, if the difference (~ 6 kcal/mol) in heat of hydrogenation of cyclohexene or cyclopentene and norbornene (15) is taken as a measure of the relief of strain in the latter on breaking the π -bond, then the addition of a bromine atom to norbornene should be exothermic by ~ 6 kcal/ mol. Since the rate of benzylic hydrogen abstraction by bromine atoms from toluene is 290 times greater than from the methylene group of propane and is exothermic to the extent of ~ 10 kcal/mol from bond dissociation energies (14), benzyl bromide should have been formed in quantity if the bromination of norbornene were exclusively a radical process, provided that the activation energies for the two reactions being considered here paralleled the energy differences between starting materials and intermediates.

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TABLE 3. Variation in composition of dibromide fraction from addition of bromine to norbornene at 0°

Concentration of		NI	Normalized % of dibromides*					Outras
(mg/ml)	Solvent	reactions	15	16	17	18	19	variables
1.0	$CCl_4(\varepsilon = 2.24)$	3	2.0-2.5	13-15	0.8	1.0	78-84	
10.		2	7–9	15-17	1.6-2.3	1.6-2.0	66-71	
430.		3	18–19	15-17	5.3-5.4	3.8-4.1	46–47	
430.		1	17	17	5.5	3.6	51.5	Toluene added
430.		2	9.8-11	19–21	4.6-5.0	3.2-3.5	60–61	DPPH (100
10.		1	13	19	4	1.3	61	Norbornene added to 10 × excess Bra
1.0	$CH_{2}Cl_{2}(\varepsilon = 9, 08)$	1	52	23 7	62	2.8	62 4	112
10 0		3	62-7.0	21-22	6.7-7.1	3 0-3 6	56-59	
215. 240		2	5.8-8.5	19-20	4–6.8	2.7-4.1	57	
430.		1	7.3	20	6.2	3.9	61.7	
1.0	$CH_3CN(\varepsilon = 37.50)$	1	1.8	11.9	<0.2	< 0.2	86.3	
5.6		1	3.1	16.2	<0.2	< 0.2	80.5	
10.0		2	2.3-3.0	13-17	0.6	2.0	77–82	
215.		1	3.6	18	<0.5	<0.5	78.5	10° instead of 0°

*The difference between 100% and the horizontal sum of % for a reaction is due to small amounts of other unidentified compounds, presumably dibromides because of their g.l.p.c. retention times, see Fig. 1 for example.

*cis-exo-*2,3-dibromonorbornane (i). An authentic sample of i was synthesized (10) and shown by mixed g.l.p.c. not to be identical with any peak from the bromination product. The absence of this isomer may be attributed to steric shielding by the bromine atom already present in cation $11.^9$

As has been pointed out by Berson (16), one of the dibromides, the 2-exo, 3-endo compound 15, may arise by two routes: normal trans addition of bromine to norbornene via bromonium ion 14 as suggested by Kwart and Kaplan (3), or else by 6,1-hydride shift¹⁰ in the initially formed cation 11 with subsequent attachment of bromide at C-2 of 12. In the present work it has been found that both processes occur simultaneously. Evidence for two ionic paths to 15 comes from bromination in methylene chloride in the presence of a large amount of bromide anion (Table 2, entry 7). The dibromo product was almost entirely the 2-exo,3-endo isomer 15 with no detectable amount of 17 or 18 and a marked decrease in 16. The increased formation of the 2-exo, 3-endo dibromide 15 in

 9 Cf. the corresponding methylnorbornyl cation in ref.

this experiment requires a mechanism allowing capture of an intermediate cation by bromide before much hydride shift has taken place. Still, the fact that *some* 2-*exo*,7-*anti* dibromide 16 from 6,1-hydride shift cation 12 is formed in all of the brominations suggests that some of the 2-*exo*,3-*endo* dibromide must also result from bromide attack on the 6,1-hydride shift cation 12.

To settle the point, an experiment with labelled norbornene was carried out. Bromination of 5,6-14C-norbornene in carbon tetrachloride at 0° gave the previously described mixture of mono- and dibromo products. Rather than separate the small amount of labelled 2-exo,3endo dibromide, advantage was taken of its greater reactivity toward dehydrobromination compared to the other four dibromides. After removal of the 2-exo-bromonorbornane and most of the bromonortricyclene by fractional distillation, the remaining mixture was treated with phenyllithium at 0° for 30 min, which conditions had been found to dehydrobrominate the 2-exo, 3-endo dibromide cleanly without affecting bromonortricyclene, 2-exo-bromonorbornane, or the other dibromides. The crude product was distilled with added decalin to remove the lower boiling 2-bromonorbornene. Ozonization of the distillate gave cis-1,3-cyclopentane dicarboxylic acid which was degraded

^{17. &}lt;sup>10</sup>In this paper for convenience the carbon atoms of cations 11-13 and 24-26 as well as bromonortricyclene 2 have been numbered to retain the generally used terms for referring to hydride shifts in the unsubstituted norbornyl cation.

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FIG. 3. Formation of norbornene bromination products. *The structure drawn is not intended to exclude the possibility of other atoms being bonded to the bromine atom.

by a modification (see below) of the customary procedure (18). The degradation results are shown in Fig. 4. If 15 arose entirely from bromonium ion 14 or from the radical process in which rearrangement would not occur, the radioactive carbon would appear exclusively in the ethylenediamine, whereas if 6,1-hydride shift occurred, label would also appear in C-2 of the cyclopentanediamine and in a carboxyl group of the derived succinic acid. The carbon dioxide from degradation of the succinic acid was radioactive but the figure given is probably the least reliable of the five,¹¹ and the value given is a

¹¹It was not certain that all carbon dioxide had been swept into the absorption solution for counting.

minimum figure (see Experimental). If this figure is disregarded, the amount of 2-exo,3endo dibromide which arises from 6,1-hydride shift is 19-27%, depending on the way in which it is calculated (see Experimental) with the rest of the dibromide 15 arising from the bromonium ion 14 and from the radical pathway. Since the radical scavenger experiments indicate that at least half of the 2-exo,3-endo dibromide is formed by a radical path in carbon tetrachloride at the high concentrations used (3-5), and since about one quarter of the 15 arises by 6,1-hydride shift, the remaining quarter is all that results from bromonium ion 14 under these conditions.

A comparison of the products isolated from

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Reagent	Solvent	Temperature (°C)		Products and	% composition	of crude prod	luct	
Br ₂	CH_2Cl_2	0	Br Br	Br Br	Br	Br	Br	Br
			Br 0.0 3.6	14.9	33.0	Br 3.7	2.3	41.5
BrNHCOMe HF	Et ₂ O/HF	- 78	Three unidentified minor products	Br F 38.0	Br 22.0	Br NHC [11.0]*	СОМе	Br 37.0
Cl_2	CCl₄	25		n	CI CI CI		_	CI
			3.5 6		25.5			65
Br ₂ NSO ₂ C ₆ H ₅	C ₆ H₅	25	Two unidentified dibromides ~8	Br NHSC ~13	$D_2 \phi$ Br NHS0 ~29	Ο ₂ φ	_	→Br ~46

TABLE 4. Comparison of norbornene ionic addition reactions

*Isolated from a separate run.

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FIG. 4. Degradation of ¹⁴C-labelled 2-bromonorbornene.

various halogenations of norbornene is given in Table 4. In comparing the chlorination and bromination reactions, which have been examined in greatest detail, the greater yield of chloronortricyclene relative to bromonortricyclene is perhaps a reflection of the greater basicity of chloride ion than bromide ion in aprotic solvents. The absence of hydride shift products in the chlorination reaction is explicable on the basis of a less stabilized (chlorine being more electronegative and less efficient at bridging than bromine) (20), and hence more reactive, initial cation reacting with the more nucleophilic (in aprotic solvents) chloride ion (however, see ref. 19).

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As mentioned in a previous publication (2), two probably related points of difference between the bromination and bromofluorination reactions deserve comment. These are the absence of 2-exo, 3-endo isomers as major products¹² and the much larger proportion of the 6,1-hydride shift product 7-anti-bromo,2-exo-fluoronorbornane in the latter reaction. Any initially formed bromonium ion in the bromofluorination reaction would presumably have a longer lifetime to undergo hydride shift since associated fluoride-hydrogen fluoride species in ether should be poorer nucleophiles than bromide anion in aprotic medium. If so, it would not be surprising to find much less product of attack on a bromonium ion and an increase in 6,1-hydride shift products. As an approximation, the proportion of 2-exo-fluoro-3endo-bromo isomer to be expected from the 6,1hydride shift cation 12 can be estimated to be the same ($\sim 10\%$ of the 7-anti isomer) as for the bromination, or only about 4% of the total product and could be present as one of the minor components.¹² The observed product yields are not likely to be the result of prior formation of a 2-exo,3-endo compound followed by rearrangement; loss of bromide from such a product would eventually lead to 7-fluoro derivatives which are not observed.

A comparison of the relative rates of anion capture at each pair of Wagner-Meerwein related sites in the three substituent-bearing nonclassical ions is presented in Table 5. Although the reactions were not all run under the same conditions, the variation in the product ratios can be accounted for by a combination of steric and inductive effects. The preponderance of 7-syn isomer from reaction of cation 24 is favored by the steric bulk of the substituent X, which would hinder formation of the more crowded 2-exo, 3-exo isomer. The difference in ratio for X = methyl vs. bromine is expected both from the electron withdrawing effect of bromine rendering C-1 relatively more positive than C-2 (compared to the reverse situation for the methyl substituted cation) and from the smaller size of the entering acetate oxygen atom (relative to bromide) when X =methyl.

In the capture of cation 25, there is no steric interaction of entering nucleophile and substituent. However, a preference for attack at C-6 when X = bromine is consistent with the expected inductive effect of bromine rendering C-6

¹²There were three unidentified minor (<3% of total) products detected during g.l.p.c. examination of the bromofluorination product. One or two of these may have been 2-exo,3-endo isomers.

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	Ratios of products							
Non-classical ion	Wagner-Meerwein product pair	X = Y = Br	$\begin{array}{l} X = Br \\ Y = F \end{array}$	X = Y = Cl	$\begin{array}{c} X = Br \\ Y = NHSO_2C_6H_5 \end{array}$	$\begin{array}{c} X = Me \\ Y = OAc \end{array}$		
x	X Y:	X Y > 66:1*	> 22:1*	7.3:1	> 29:1*	5:1		
24 6 25		Y 8:1†	> 38:1§	_	> 13:1§	1.08:1		
6 1 2 26 X	Y : Y	X 1.6:1‡		_	_	1.23:1‡		
*7 3-020 020 1005								

TABLE 5. Ratios of attack at Wagner-Meerwein related sites

*2,5-exo,exo was not detected, †Based on amount of 15 formed by hydride shift only. Insensitive to solvent. §No 2-exo,3-endo detected.

more electron deficient and therefore relatively more reactive than C-2. To harmonize this rationale with the result (approximately equal attack at both sites) for the same cation when X = methyl requires the introduction of some factor (torsional effect of the methyl with C-2 hydrogen being pushed up?) to explain why there is not more attack at C-2 in this case.

For cation 26, in which not only is direct interaction of entering nucleophile and substituent X not possible, but also the inductive effect through bonds (not through space, however) would be the same for both C-1 and -6, the distinction between the two positions is almost negligible and the ratio of capture for X = bromine and methyl approaches unity.¹³

The effect of solvent on the bromination reaction was examined because of the previous reports^{3,4,5} of the effect of added pyridine. In the present work it was found that the effect of pyridine and pyridine derivatives is much too complex to be accounted for by a simple solvent effect (1). However, when the solvent was changed from carbon tetrachloride to the more polar methylene chloride and acetonitrile, the relative constancy of the dibromide product composition was consistent with purely ionic bromination.

With the bromination of norbornene rationalized, a related reaction, the bromination of *exo*trimethylene-2-norbornene (22), was also reexamined. In agreement with the previous report (21) we find that in carbon tetrachloride the major product (80%) is the 2-*exo*,3-*endo* dibromide 23 accompanied by minor amounts of at least seven other compounds. This same product was formed in the same 80% yield when the bromination was conducted in pyridine, but the proportions of the minor products changed (see Experimental). The minor products were not further investigated.



Improvement in Norbornene Degradation

The standard four-step procedure (18) for degradation of norbornene involving alternating

¹³We refrain from speculating here on reasons for the small but real difference from unity, but see ref. 1.

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TABLE 6.	Properties of norbornene dibromides*

Peak				Analysis found(%)			
	Compound	% Purity (g.l.p.c.)	$\mu_{\text{cyclohexanc}}^{25}$	C (Calcd. 33.09)	H (Calcd. 3.97)	Br (Calcd. 62.89)	
1	2-exo.3-endo-Dibromonorbornane (15)	99	2,60	33.29	3.91	62.76	
2	7-anti,2-exo-Dibromonorbornane (16)	97	2.42	32.89	4.09	63.25	
3	2-exo.5-endo-Dibromonorbornane (17)	91	1.10	33.22	4.05	62.72	
4	2-exo,5-exo-Dibromonorbornane (18)	> 99	0.66	33.05	3.94	62.60	
	7-syn,2-exo-Dibromonorbornane (19)	98	3.30	33.43	4.03	62.65	

General

*For the i.r. spectra see ref. 1.

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oxidation and Schmidt reactions suffers from low yields. In the present work the yields and convenience of the first and last steps have been improved. In the first step, when ozone instead of permanganate was used as the oxidizing agent in ethyl acetate at $\sim -70^\circ$, 87-99% yields of 1,3-cyclopentane dicarboxylic acid were obtained in agreement with previous work (22). The acid was a mixture of 92% of the *cis* isomer and 8%of an impurity which was not the trans isomer, but which was removed by recrystallization. Ethyl acetate was used as the ozonization solvent to avoid the formation of some monomethyl ester which occurred in methanol.

The second step, the Schmidt reaction on the diacid, proceeds well as described in the literature (18), but the third step, the oxidation of the cyclopentane-1,3-diamine to succinic acid has always been troublesome. Since succinic acid is stable to aqueous Cr^{6} (23), this oxidizing agent was tried, but the reaction was capricious and the isolated yields were never more than 27%. On the possibility that initially formed succinic acid (or the diamine) was being oxidized further by Cr^5 or Cr^4 (24), oxidations were tried with Cr⁶ in the presence of Mn² as scavenger for Cr⁵ and Cr⁴ (25), but the yield of succinic acid was still only 26%, which is about the yield obtained from oxidation by permanganate. In control experiments it was shown that succinic acid was recovered in over 90% yield from the Cr⁶-Mn² reagent, and therefore the cyclopentane-1,3diamine is oxidized by Cr⁶ mainly to products not degraded to succinic acid.

The final step in the degradation sequence, the Schmidt reaction on succinic acid has been reported to go in only 8% yield (26), and for this reason the alternative Curtius degradation via the azide and urethane has been employed (27). This procedure, although a big improvement, is tedious and gives only 50% of the diamine. Since in succinic acid each carboxyl group may be considered as an electronegative substituent in close proximity to the other, it seemed that the Stothers-McNamara modification (28) of the Schmidt reaction might give better results. These workers found that the use of 20% oleum in the reaction with electronegatively substituted aromatic acids gave much better yields of carbon dioxide. When this procedure was applied to succinic acid, yields of 41-83 % of barium carbonate and 30-51% of the dibenzamide derivative of ethylenediamine were realized. Although the yield of diamine from the modified Schmidt reaction is no better than from the Curtius procedure, the Schmidt procedure is more economical.

Experimental

Experimental details are the same as in ref. 2 with the following additions. For gas chromatography a Glowall Model 400 instrument equipped with a heated exit port and a hydrogen flame detector was employed. Its all glass column and injection chamber was a 1.8 m length of coiled 3.4 mm i.d. (analytical) or else 10 mm i.d. (preparative) tubing. Helium or argon was used as the carrier gas. For preparative work a 50:1 stainless steel splitter was used in conjunction with the 10 mm column. FFAP refers to Wilkens free fatty acid phase and DEGS to diethylene glycol succinate. The response of the hydrogen flame detector to the five dibromides and 2 and 20 was determined by analysis of synthetic mixtures of known weight percent (see ref. 1 for details). No correction factor was necessary for the dibromides to convert peak areas to weight percent, but an average factor of 0.81 was required for 2-exo-bromonorbornane.

For integration of the g.l.p.c. charts, the amount of 2 and 20 relative to the total dibromide area was determined by the cut-and-weigh technique or by planimeter from a trace in which all peaks were on scale. Dibromide ratios were obtained from a second trace in which the height of the dibromide peaks was optimized.

Melting points were taken on a Reichert Kofler microscope hotstage unless otherwise specified. Refractive indices were measured on a Bausch and Lomb refractometer. Microanalyses were performed in the laboratories of A. Bernhardt, Mülheim, Germany, and A. B. Gygli, Toronto.

The ¹⁴C counting was carried out with a Nuclear Chicago MK1 liquid scintillation counter. The "TFC' scintillation solution (29) used for counting was prepared by diluting 5 volumes of toluene containing 0.4% PPO (2,5-diphenyloxazole) and 0.005% bis-MSB [p-bis(omethylstyryl)-benzene] with 4 volumes of methyl cellosolve (ethylene glycol monomethyl ether); samples were weighed (see Table 10) into scintillation vials and counted in 15 ml of TFC. Barium carbonate was counted by trapping the acid-liberated ¹⁴CO₂ in a scintillation vial containing 1.0 ml of NCS (a quaternary ammonium base, 0.6 N in toluene, supplied by Nuclear-Chicago Corp.) and then adding 15 ml of TFC for counting. Samples were counted at balance point in a 0.5-9.9 V window, using a channels ratio method to ensure that counting efficiency did not change from sample to sample. As there was no variation in counting efficiency, counts per min data were adequate for comparison.

In view of the fatalities which have occurred in work with closely related dibromo compounds (30), all operations with the dibromonorbornanes, including g.l.p.c., were conducted in a fume cupboard.

Dibromonorbornanes

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The procedure of Kwart and Kaplan (3) was used. Norbornene¹⁴ (20 g, 0.21 mol) in 40 ml of carbon tetrachloride was cooled to -10° with an ice-salt bath. A solution of 29 g (0.18 mol) of bromine in 20 ml of carbon tetrachloride was added with stirring at a rate such that the temperature remained at or just below 0°. After 30 ml of the bromine solution had been added, the persistence of red color and lack of exothermicity indicated that the olefin had been consumed. Evaporation of solvent left 40.4 g of crude product whose g.l.p.c. (Fig. 1) at 130° on a column of 5% DEGS on 60-80 mesh Chromasorb P indicated the presence of at least seven major components and three minor ones.

Bromonortricyclene and 2-exo-bromonorbornane, two of the major products, were separated as the lowest boiling (b.p. 60° at 11 mm) materials by fractional distillation on a 45 cm Nester and Faust platinum spinning band column. The mixture of higher boiling dibromides (b.p. 30-75° at 0.06 mm) was separated by preparative g.l.p.c. on a column of 10% FFAP on non acid-washed 60-80 mesh Chromasorb P. Operating conditions: injector temperature 270°, column temperature 170°, exit port temperature 200°, argon carrier gas flow rate ~ 80 ml/min, 40-50 µl of dibromide mixture per injection. Fractions collected were re-injected and the other five major products (numbered in order of elution) were obtained in the purity indicated in Table 6. Peak 4 (2-exo,5exo-dibromonorbornane) was obtained as a crystalline solid, m.p. 94-95.5°, after recrystallization from petroleum ether (b.p. 30-60°).

¹⁴Norbornene (Aldrich Chemical Co.) was purified by distillation. It gave a single g.l.p.c. peak on a column of 5% DEGS on Chromasorb P. The purity must be checked regularly because even purified norbornene gives rise to higher boiling material on long standing.

Isomerization of Dibromonorbornanes

(a) A mixture of 418 mg of 7-syn,2-exo-dibromonorbornane (19) and 1 ml of 47% aqueous hydrobromic acid was refluxed for 3.25 h (cf. refs. 3 and 4). The resulting dark-colored mixture was cooled and extracted with 10 ml of ether and analyzed by g.l.p.c. to yield the following composition: 15, 15.2%; 16, 34.5%; 17, 22.8%; 18, 21.3%; 19, 0.5%; 3 minor products (one in the starting material), total 6.0%. On shorter reflux times (1.5-2 h) the amount of 16 was greater at the expense of 17 and 18.

(b) Hydrogen bromide gas was passed continuously at room temperature into a solution of 67 mg of the 7-syn,2exo isomer 19 in 3 ml of carbon tetrachloride. Samples were withdrawn at intervals and analyzed by g.l.p.c. for the ratios of 15:16:17:18 (see Table 7).

(c) Each of the purified dibromides was treated with 5 ml of a standardized solution of hydrogen bromide in methylene chloride¹⁵ at 0°. After the allotted time, the reaction was quenched with 2 ml of 10% aqueous sodium bicarbonate solution. The separated and dried organic layer was analyzed by g.l.p.c. and the results are summarized in Table 8.

Reaction of Bromonortricyclene with Hydrogen Bromide

Bromonortricyclene was treated with standardized solutions of hydrogen bromide in methylene chloride.¹⁵ After the allotted time the reaction was quenched with aqueous sodium bicarbonate solution. The separated and dried organic layer was analyzed by g.l.p.c., and the results are summarized in Table 9. The kinetically controlled product from the 58% reaction entry had the following composition: 15, 3.3%; 16, 29.3%; 17, 33.1%; 18, 18.4%; 19, 15.9%.

Brominations under Other Conditions

(a) With Calcium Carbonate

A solution of 543 mg (5.8 mmol) of norbornene in 100 ml of methylene chloride¹⁵ was cooled to 0° and stirred vigorously (magnetic bar) with 5.0 g of suspended powdered calcium carbonate. A solution of 1.0 g (6.25 mmol) of bromine in 5 ml of methylene chloride was added during 20 min. Then 5 ml of 10% sodium bicarbonate solution was added, followed by 25 ml of water. Suspended solid was removed by filtration, and the organic layer was filtered and dried. After removal of solvent, the crude product was analyzed by g.l.p.c. (entry 5, Table 2). In an attempt to diminish further the amount of 2-exobromonorbornane the reaction was repeated with 25.0 g

Table 7.	Products of reaction of	19
	with HBr	

Compound	3 h	20 h	25 h
15 16 17 18	12.7 54.9 17.8 14.6	14.3 49.8 19.3 16.5	16.8 39.8 24.0 19.2

¹⁵Except where carbon tetrachloride was used to reproduce exactly the conditions of Kwart and Kaplan (3), methylene chloride was generally substituted because of its lower freezing point and because of the greater solubility of hydrogen bromide and salts in this solvent.

The g.l.p.c. resul	Time (h)	mg HBr/5 ml	Weight (mg)	Compound
No isomerization	17	31	25.0	15
No isomerizatior	17	31	25.0	16
No isomerizatior	17	31	14.0	17
No isomerization	17	31	18.0	18
No isomerizatior	5	31	19.6	19
or at most a trace (<4%)				
No isomerization	14.5 (25°)	42/1 ml	7.4	19
No isomerizatior	ì	13.4/2 ml	15.0	i

TABLE 8. F	Reaction	of dibron	nides v	vith I	Br
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TABLE 9. Reaction of bromonortricyclene with HBr

mg of 2	Time (h)	Temperature (°C)	mg HBr	Volume (ml)	The g.l.p.c. result
76.4	73	0	43.5	25	No reaction
5 µl	0.33	25	6.6	1	No reaction
6.5	1.0	25	20.2	1	Slight reaction
5	14.5	25	42	1	58% reaction
7.4 of 19	14.5	25	42	1	No isomerization

of calcium carbonate to give 1.17 g (98%) of crude products (entry 6, Table 2).

(b) Dilution

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The above experiment (a) was repeated without calcium carbonate on two different solutions of norbornene in methylene chloride,¹⁵ one containing 498 mg in 100 ml and the other containing 481 mg in 2 ml. The reactions were quenched with aqueous sodium bicarbonate solution, and the organic layers were separated and dried over magnesium sulfate. The g.l.p.c. analyses of the crude products are entries 1 and 2 in Table 2.

(c) With Oxygen Scavenger

Oxygen was passed through a sintered glass bubbler into a vigorously stirred (magnetic bar) solution of 518 mg of norbornene in 100 ml of methylene chloride¹⁵ maintained at 0°. A solution of 1.0 g of bromine in 2 ml of methylene chloride was added during 20 min. The reaction was worked up as in (b). The g.l.p.c. analyses gave the figures in entry 4 in Table 2.

(d) With Toluene

To a stirred (magnetic bar) solution of 526 mg (5.6 mmol) of norbornene and 2.415 g (26.2 mmol) of toluene in 100 ml of methylene chloride¹⁵ maintained at 0.5– 1.5° was added during 20 min a solution of 350 mg (2.19 mmol) of bromine in 2 ml of methylene chloride. The g.l.p.c. analysis showed that the dibromide products were formed in the same ratios as in the absence of toluene and that the small peak corresponding in retention time to benzyl bromide constituted less than 0.5% of the total products. The experiment was repeated with carbon tetrachloride solutions (see Table 3).

(e) With Other Solvents

Small scale brominations were run in carbon tetrachloride and acetonitrile as well as in methylene chloride. The general procedure was to add the bromine diluted with a little of the solvent to a stirred (magnetic bar) solution of norbornene in the solvent. The reaction mixture was washed with aqueous bicarbonate and analyzed by g.l.p.c. The total area under peaks in the dibromide region was equated to 100%, and the normalized percents of compounds 15–19 were calculated on this basis. The results are summarized in Table 3. Reactions in acetonitrile and in the more concentrated carbon tetrachloride solutions gave rise to variable amounts of a g.l.p.c. peak (different for the two solvents) suspected to arise from involvement of solvent in the reaction.

(f) With Diphenylpicrylhydrazyl

To a solution of 430 mg of norbornene in 1 ml of carbon tetrachloride was added 100 mg of diphenylpicrylhydrazyl. The radical was only partially soluble. Neat bromine $(20 \ \mu$ l) was added dropwise at 0° with vigorous stirring by a magnetic bar. The reaction mixture was analyzed by g.l.p.c. Control experiments showed that diphenylpicrylhydrazyl had no effect on the dibromides, and also that the preformed product of bromine plus the radical acting on norbornene gave the same proportion of dibromides as bromine alone acting on norbornene at a given concentration (see Table 3).

(g) $At - 78^{\circ}$

To a solution of 510 mg (5.4 mmol) of norbornene in 100 ml of methylene chloride¹⁵ cooled to -78° by a Dry-Ice – acetone bath was added with stirring (magnetic bar) during 20 min 1.0 g (6.2 mmol) of bromine dissolved in 2 ml of methylene chloride. The reaction was quenched with 5 ml of 10% aqueous sodium bicarbonate, and the separated organic layer analyzed by g.l.p.c. (entry 3, Table 2).

(h) With Tetraethylammonium Bromide

A solution of 68.8 mg (0.73 mmol) of norbornene in 10 ml of methylene chloride¹⁵ was saturated with tetraethylammonium bromide (1.271 g, 6.05 mmol) at 0°. Bromine (0.20 g, 1.2 mmol) was added with stirring (magnetic bar) during 3 min at -5 to -3° . The mixture was allowed to stir at 0° for 17 min more. Work-up gave 157 mg of crude product whose g.l.p.c. analysis is entry 7, in Table 2.

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TABLE 10. Counting results from degradation of ¹⁴C-labelled norbornene and dibromonorbornane*

	Weight (mg) counted		Counts (min ⁻¹ \times 10 ⁻³)		Counts (min ⁻¹ mmol ⁻¹ \times 10 ⁻⁵)	
Compound	A	<u></u>	A	B	A	В
1,3-Cyclopentane						
dicarboxylic acid	2.89	5.72	21.3	20.0	11.6	5.53
1,3-Cyclopentanediamine						
dibenzamide	3.18	3.21	11.3	5.93	10.9	5.70
Succinic acid	1.34	2.30	12.2	9.59	10.7	4.93
Barium carbonate	6.75	1.70	0.0	0.172	0.0	0.20
Ethylenediamine						-
dibenzamide		2.38		3.91		4.39

*All samples were counted to 105 total counts. A, Norbornene control degradation; B, degradation of 2-exo,3-endo dibromide 15 from

Hydrogenolysis of 7-syn,2-exo-Dibromonorbornane (19)

Tetrahydrofuran (10 ml), t-butyl alcohol (2.1 ml, 22 mmol), and finely chopped sodium (1.5 g, 63 mga) were heated to reflux with stirring. 7-syn,2-exo-Dibromonorbornane (19) (1.01 g, 4.0 mmol) was added and the resulting dark solution was refluxed for 45 h. After dilution with water and extraction with ether, the organic solution was slowly distilled until the distillation temperature reached 40° when norbornane just began to sublime. The residual 1.00 g of liquid, containing some solvent, on analysis by g.l.p.c., was shown to contain 110 mg (30%) of norbornane. A sample was isolated by preparative g.l.p.c. and shown to be identical (i.r. spectrum, g.l.p.c. retention time) with an authentic specimen.

cis-1,3-Cyclopentanedicarboxylic Acid

A solution of 5.86 g (62 mmol) of norbornene in 150 ml of ethyl acetate was cooled to $\sim -78^\circ$ in a Dry-Ice – acetone bath, and ozone was passed in until a blue color persisted. The solution was allowed to warm to room temperature, and the solvent was evaporated at reduced pressure on a rotating evaporator. The residual viscous oil was warmed with a mixture of 50 ml of 98% formic acid and 30 ml of 30% aqueous hydrogen peroxide solution, whereupon a vigorous exothermic reaction occurred at $\sim 60^{\circ}$ which caused the solution to reflux. Reflux was maintained for 1 h before the solution was evaporated to leave 9.53 g (97%) of a viscous oil which slowly solidified, m.p. $87-107^{\circ}$. The g.l.p.c. analysis of the methyl ester gave two peaks showing this material to be 92% of cis-diacid and 8% of an impurity. The impurity was not the trans-diacid since methoxide-catalyzed epimerization of the methyl ester of pure cis-diacid gave two isomers of g.l.p.c. retention times: 6.0 min (trans-dimethyl ester) and 7.5 min (cis-dimethyl ester) neither of which was identical with the impurity of retention time 4.5 min. However, the impurity was removed by recrystallization from ether - petroleum ether (b.p. 30-60°). Four such recrystallizations gave colorless diacid, m.p. 118-120° (lit. (22b): 121.5-122.5°).

Dehydrobromination of 2-exo, 3-endo-Dibromonorbornane (15)

Pure (97%) 15 (101 mg) was treated under nitrogen at ice bath temperature with 0.75 ml of a 1.5 M solution of phenyllithium in benzene-ether (Alfa Inorganics). Samples withdrawn for g.l.p.c. showed complete reaction after 15 min. The n.m.r. spectrum of the solution had a vinyl proton doublet at 5.81 p.p.m. different from the vinyl proton absorption of added norbornene at 5.92 p.p.m. (dd).

In separate experiments it was demonstrated that 2 and 16-20 did not react with phenyllithium under the conditions used for 15 (see ref. 1).

Degradation of Radioactive 2-exo, 3-endo-Dibromonorbornane (15)

(a) 1,3-Cyclopentanedicarboxylic Acid

Norbornene-5,6-14C (752 mg, 1 mCi) supplied by Mallinckrodt Nuclear, Orlando, Florida, and synthesized by the Diels-Alder addition of ethylene-1,2-14C to cyclopentadiene (31) was dissolved in 100 ml of carbon tetrachloride. A 1 ml aliquot was diluted with inactive norbornene and degraded to prove that the ¹⁴C was entirely at C-5 and -6. See Table 10.

An aliquot of this radioactive norbornene solution (20 ml, \sim 200 µCi) was diluted with inactive norbornene (20.24 g, 0.22 mol) in 20 ml of carbon tetrachloride and cooled in an ice-salt bath. A solution of 34 g (0.21 mol) of bromine in 23 ml of carbon tetrachloride was added with stirring (magnetic bar) at a rate which kept the temperature between -2 and $+2^\circ$. After ~ 1.25 h when the reaction solution retained the bromine color, addition of bromine was stopped and the solvent was removed at reduced pressure and room temperature. Most of the monobromides 20 and 2 were distilled at 72° (16 mm) to leave 38.23 g of dibromides containing some 2 and 20. The g.l.p.c. analysis calculations gave 2.64 g (6.9%) of 2-exo,3-endo-dibromide 15 in this mixture. The normalized percents of the dibromonorbornanes were 15 (9.8%), 16 (20.5%), 17 (4.1%), 18 (3.6%), and 19 (62%); the difference between these figures and those for the 430 mg/ml reaction in Table 3 may be due to differences in instantaneous bromine/norbornene ratio for the large vs. small scale reaction. To this mixture, which was cooled under nitrogen in an ice bath, was added 75 ml of 1.9 M phenyllithium solution through a rubber septum. After 30 min the solution was cautiously quenched with 10 ml of aqueous sodium hydroxide. The g.l.p.c. of the organic layer showed 15 to have been completely destroyed, but the ratios of 16:17:18:19 remained the same. The aqueous layer was separated and the benzene-ether solvent removed under reduced pressure at room temperature. Decalin (20 ml) was added and distillation (a Bunsen burner was used to limit frothing) was carried out until a temperature of 80° (16 mm) was reached. A further 30 ml of decalin was added and the distillation continued until approximately 30 ml of distillate (receiver cooled in

an ice bath) had been collected. The distillate was diluted with 25 ml of ethyl acetate, and the solution cooled in a Dry-Ice - acetone bath. Ozone was passed into the stirred (magnetic bar) solution for 90 min by which time the solution was pale green. After evaporation of the solvent, 25 ml of 98% formic acid and 15 ml of 30% aqueous hydrogen peroxide was added, and the mixture gently warmed until reaction was initiated as indicated by gas evolution. When the exothermic reaction subsided, the mixture was heated on a steam bath for 30 min. After evaporation of most of the formic acid the solution was cooled and extracted with 10% aqueous sodium hydroxide. Acidification with 20% hydrochloric acid, saturation with sodium chloride, and extraction with six 30 ml portions of ether afforded 865 mg (57%) of a pale brown oil which slowly solidified. A sample recrystallized from ethyl acetate had m.p. 121-122° (lit. (22b): 121.5-122.5°).

(b) 1,3-Cyclopentanediamine Hydrochloride

The 865 mg of crude active diacid was diluted with 720 mg of inactive acid by solution in ethyl acetate and evaporation. A portion (1.43 g, 9.05 mmol) of the resulting acid was dissolved in 15 ml of 100% sulfuric acid in a 50 ml flask. The flask was equipped with a gas outlet attached to a wash bottle containing dilute aqueous chromic acid, a side arm for addition of solid sodium azide, and a nitrogen inlet projecting below the surface of the solution. After the system was flushed with dry nitrogen, the chromic acid wash bottle was attached to a wash bottle containing carbon dioxide free sodium hydroxide solution. Sodium azide (2.5 g, 38.5 mmol) was added as the solution was stirred (magnetic bar) and heated to 40-45°. After the addition (\sim 0.75 h) a slow stream of nitrogen was passed through the system for a further 30 min. The carbon dioxide absorbed in the sodium hydroxide solution was precipitated as barium carbonate by treatment with 25 ml of a solution of barium chloride and ammonium chloride (0.33 M in each). The yield of barium carbonate after filtration and drying at 120° for 6 h was 2.114 g (59%).

The sulfuric acid solution was carefully neutralized with \sim 30 ml of 50% aqueous sodium hydroxide and the resulting solution distilled to dryness into 20 ml of 15% hydrochloric acid. Water (30 ml) was added to the residue and the resulting mixture again distilled to dryness; this procedure was repeated six times. Failure to distill almost to complete dryness results in very low yields. The aqueous distillate after evaporation afforded 819 mg (53%) of 1,3-cyclopentanediamine hydrochloride as a buff powder. Yields in other experiments ranged between 40 and 92%.

The *dibenzamide* derivative used for counting was obtained by vigorously shaking a solution of 51 mg (0.29 mmol) of the diamine hydrochloride in 3 ml of 10% aqueous sodium hydroxide with 0.15 ml of benzoyl chloride. The white precipitate was filtered, and the filtrate extracted with two portions of ether. The material (87.7 mg, 97%) from the combined precipitate and ethereal extracts was recrystallized thrice from ethanol to give colorless needles, m.p. 213.5–215° (lit. (18): 213–215°).

(c) Succinic Acid

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Potassium permanganate (6.21 g) was added to a solution of 770 mg (4.45 mmol) of the diamine hydrochloride

prepared in (b) in 60 ml of water. The reaction was heated in an oil bath $(130-140^\circ)$ for 15 min, cooled, and acidified with 5 ml of 10% hydrochloric acid. Sulfur dioxide was passed in until the solution was clear and colorless. Continuous ether extraction for 42 h afforded 146 mg (28%) of pale yellow solid succinic acid. The g.l.p.c. of the dimethyl ester of the crude acid indicated the absence of other components. Five recrystallizations from ethyl acetate gave colorless needles, m.p. 175-185°.

(d) Ethylenediamine Dibenzamide

Several variations in reaction procedure were tried, and it was found that failure to follow exactly the procedure described below frequently resulted in very low or no yield of the dibenzamide.

The same apparatus was used as described in (b) for the preparation of 1,3-cyclopentanediamine. A solution of 20 mg (0.17 mmol) of recrystallized succinic acid from (c) in 1 ml of 20% oleum was prepared in the 50 ml flask and warmed to 40°. The apparatus was flushed with dry nitrogen before attachment of the wash bottle containing sodium hydroxide. Sodium azide (104 mg, 1.6 mmol) was added *rapidly* (~1 min addition time) to the stirred solution (magnetic bar) at 40°. After the vigorous reaction was over, the flow of nitrogen was maintained for 60 min. The carbon dioxide was precipitated as barium carbonate from 10 ml of ammonium chloride – barium chloride solution (0.33 M in each). The yield of barium carbonate after filtration and drying was 27.3 mg. (41%).

The sulfuric acid solution was chilled in an ice bath, diluted with 6 ml of water, and carefully basified with 3 ml of 50% aqueous sodium hydroxide. The solution was allowed to warm to room temperature and water was added to dissolve any precipitated salts. Benzoyl chloride (0.10 ml) was added and the mixture shaken vigorously until a white precipitate formed. Filtration, water washing, and solution in ethanol gave 23.0 mg (51%) of crude dibenzamide after evaporation of the ethanol. Recrystallization from ethanol-water gave 10 mg of white needles, m.p. 259-260° (capillary) (lit. (32): 249°), undepressed on admixture with an authentic specimen.

Calculation of the Amount of 2-exo,3-endo-Dibromonorbornane (15) Formed by 6,1-Hydride Shift

$$\frac{2(\text{act. cyclopent. diacid} - \text{act. succinic}) \times 100}{\text{act. cyclopent. diacid}} = 22\%$$

2(act. diamine – act. succinic) \times 100 act. diamine = 27%

 $\frac{(act. cyclopent. diacid - act. ethylenediamine) \times 100}{act. cyclopent. diacid} = 21\%$

(act.	diamine	 act.	ethylenediamine)	х	100	_	720/	
		act.	diamine			-	23/0	

$$\frac{2(\text{act. succinic} - \text{act. ethylenediamine}) \times 100}{\text{act. cyclopent. diacid}} = 20\%$$

$$\frac{2(\text{act. succinic} - \text{act. ethylenediamine}) \times 100}{\text{act. diamine}} = 19\%$$

Chromic Acid Oxidation of 1,3-Cyclopentanediamine

(a) To show that succinic acid could be recovered in good yield from chromic acid oxidation, 121 mg of pure succinic acid was dissolved in 7.5 ml of the oxidation reagent prepared by dissolving 33.6 g of chromium trioxide in 200 ml of water and 50 ml of concentrated sulfuric acid. The control mixture was diluted with water

and continuously extracted with ether for 46 h. The ether solution was dried over sodium sulfate and evaporated to leave 111 mg (93% recovery) of succinic acid which was found to be pure by g.l.p.c. of its methyl ester. From another control reaction refluxed for 1.5 h the recovery was 89%

(b) 1,3-Cyclopentanediamine hydrochloride (379 mg, 2.19 mmol) was dissolved in 25 ml (33 mmol) of the chromic acid solution prepared in (a), and the resulting mixture was refluxed for 1.5 h. The oxidation mixture was then cooled, diluted with 120 ml of water, and extracted continuously with ether for 41 h. Evaporation of the dried ethereal solution left 70 mg (27%) of white crystalline succinic acid, m.p. 185-188°.

(c) 1,3-Cyclopentanediamine hydrochloride (250 mg, 1.45 mmol) was dissolved in 16.5 ml (22 mmol) of the chromic acid solution prepared in (a) to which had been added 4.0 g (23 mmol) of manganous sulfate. The reaction mixture was refluxed for 1.5 h, cooled, and the excess chromic acid destroyed with sodium sulfite. Continuous ether extraction for 40 h yielded 46 mg (26%) of crystalline succinic acid.

Bromination of exo-Trimethylenenorbornene

exo-Trimethylenenorbornene was prepared from dicyclopentadiene by the procedure of Cristol et al. (33). The purity of the crystalline precursor, 2-exo-benzoyloxy-5,6-exo-trimethylenenorbornane, was carefully checked by n.m.r. spectroscopy and had m.p. 71-72° (lit. (33): m.p. 71.5-72°). The liquid olefin obtained on pyrolysis had n_{D}^{25} 1.4940 (lit. (33): n_{D}^{25} 1.4943) and gave a single g.l.p.c. peak (>98%) on a column of 5% DEGS/Chromasorb P. The i.r. spectrum of a liquid film showed no discernible peaks at 6.08, 7.42, 8.06, or 8.74 µ from the endo isomer. The phenyltriazole derivative melted at 137-143° indicating < 5% endo-trimethylene derivative present (33).

(a) In Carbon Tetrachloride

A solution of the olefin (4.31 g, 32 mmol) in 50 ml of carbon tetrachloride was cooled in an ice-salt bath, and a solution of 5.0 g (31 mmol) of bromine in 10 ml of carbon tetrachloride was added during 45 min with stirring (magnetic bar) at such a rate that the reaction temperature remained between -3 and 0°. The crude product (11.33 g) was analyzed by g.l.p.c. on a 5% DEGS/ Chromasorb P column after removal of solvent and found to contain 80% of 23 and a total of 20% of seven other components. For spectra and further details see ref. 1.

(b) In Pyridine

To a cooled solution of the olefin (3.84 g, 28.6 mmol) in 50 ml of reagent grade pyridine (dried over potassium hydroxide) was added with stirring (magnetic bar) during 15 min a solution of 5 g (31 mmol) of bromine at a rate which kept the temperature between -5 and -1° . The solution was stirred at 0° for a further 45 min. The reaction mixture was diluted with 100 ml of ether and extracted with eight 100 ml portions of water. Evaporation of the dried solution left 4.58 g of liquid product which was analyzed by g.l.p.c. on a 5% DEGS/Chromasorb P column and found to contain 80% of 23 and a total of 20% of six other compounds which were not all identical in retention times with the products formed in carbon tetrachloride. For further details see ref. 1.

A pure (>98% by g.l.p.c.) sample of the major prod-

uct, 2-exo,3-endo-dibromo-5,6-exo-trimethylenenorbornane, was obtained by vacuum distillation of the product from a larger scale pyridine reaction.

Control Comparison with exo, cis-2,3-Dibromonorbornane (i)

A specimen of authentic exo, cis-2, 3-dibromide i was prepared by the Diels-Alder procedure of LeBel (10) and had m.p. 60.5-60.8° (lit. (10): 60.4-61.3°). The g.l.p.c. comparison (admixture) showed that the compound was not identical with any of the components of the bromination mixture. On a 5% DEGS/Chromasorb P column at 150° the following retention times (min) were observed: 15 (4.0), minor component (4.6), 16 (4.9), 17 (6.15), 18 (7.1), minor components (8.75 and 9.5), i (10.2), and 19 (12.0).

A sample of 15 mg of exo, cis-2, 3-dibromide i was dissolved in 2 ml of a solution of hydrogen bromide in methylene chloride (6.7 mg/ml) previously cooled to 0°. The reaction mixture was allowed to stand for 1 h at 0°, and was then diluted with methylene chloride, washed with aqueous sodium bicarbonate, and dried over magnesium sulfate. Evaporation of the solvent left 13 mg of residual i whose g.l.p.c. trace was identical with starting material; there was no additional peak present.

The authors would like to thank Professor W. A. Ayer, Edmonton, Alberta, through whose courtesy the 100 MHz n.m.r. spectra and decoupling data were obtained, Professor R. K. Chan for help with the dipole moment measurements, Professor J. A. Berson for helpful discussions, and the National Research Council of Canada for financial support.

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