The Formation of the 2-Bicyclo[3.1.0]hexyl Cation by Deamination and Solvolysis,[1] and the Effect of Methyl Substitution at C-5

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Deamination of *endo*- and *exo*-2-aminobicyclo[3.1.0]hexanes (7) and (8) and solvolysis of the corresponding 2-chloro-compounds (1) and (2) yield very similar ratios of products showing the intervention of a common 2-cation. Rate studies of solvolysis of 2-substituted bicyclohexyl derivatives and some 5-methyl-substituted compounds indicate that the normal rate-enhancing effect of the cyclopropyl group is due to delocalisation of the symmetrical homoallyl type for *endo*- and *exo*-leaving groups. Deuterium scrambling from the 5-position was not observed in solvolysis of chlorides (1) and (2).

SINCE the early reports on the ready interconversion of cyclopropylcarbinyl, cyclobutyl, and homoallyl derivatives,[2] considerable efforts have been made to define the non-classical intermediates involved. The subject is well covered by reviews.[3] Prompted by the report of the solvolytic behaviour of 6α- and 6β-*i*-steroid derivatives,[4] we wished to generate cyclopropylcarbinyl cations within a simple but rigid system to establish the stereoelectronic influences on the interaction between the developing charge and the neighbouring cyclopropyl group. 2-Substituted bicyclo[3.1.0]hexanes were readily accessible compounds for study.

A recent report [5] of work closely related to our own [1] prompts publication now.

Tosyl esters of the epimeric bicyclo[3.1.0]hexan-2-ols (4) and (5) were found too reactive for convenient isolation.[6] The corresponding *endo*- (1) and *exo*-2-chlorobicyclohexanes (2), were then chosen, as g.l.c. techniques could be used for analysis and purification (although not without difficulty).

Reduction of bicyclohexan-2-one (3) with sodium borohydride gave a mixture of the epimeric 2-alcohols containing 93% *endo*-derivative (4).[7] This mixture on

[1] Preliminary communication, P. R. Brook, R. M. Ellam, and A. S. Bloss, *Chem. Comm.*, 1968, 425.

[2] (*a*) J. D. Roberts and R. H. Mazur, *J. Amer. Chem. Soc.*, 1951, **73**, 2509; (*b*) R. H. Mazur, W. N. White, D. A. Semenow, C. C. Lee, M. S. Silver, and J. D. Roberts, *ibid.*, 1959, **81**, 4390; (*c*) K. L. Servis and J. D. Roberts, *ibid.*, 1964, **86**, 3773; (*d*) 1965, **87**, 1331.

[3] 'Carbonium Ions,' eds. G. A. Olah and P. von R. Schleyer, Wiley-Interscience, New York, 1972, vol. III, contains three reviews, (*a*) 'Homoallylic and Homoaromatic Cations,' P. R. Storey and B. C. Clark, p. 1007; (*b*) 'Cyclopropylcarbonium Ions,' H. G. Richey, p. 1201; (*c*) 'Cyclopropylcarbinyl and Cyclobutyl Cations,' K. B. Wiberg, B. A. Hess, and A. J. Ashe, p. 1295; (*d*) see also M. Hanack and H. J. Schneider, *Angew. Chem. Internat. Edn.*, 1967, **6**, 666; (*e*) B. Capon, *Quart. Rev.*, 1964, **18**, 45.

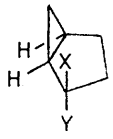
[4] E. M. Kosower and S. Winstein, *J. Amer. Chem. Soc.*, 1965, **78**, 4347, 4354; 1959, **81**, 4399.

[5] E. C. Friederich and M. A. Saleh, *Tetrahedron Letters*, 1971, 1373; *J. Amer. Chem. Soc.*, 1973, **95**, 2617.

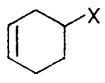
[6] E. C. Friederich, M. A. Saleh, and S. Winstein, *J. Org. Chem.*, 1973, **38**, 860.

[7] For related reductions see E. J. Corey and R. L. Dawson, *J. Amer. Chem. Soc.*, 1963, **85**, 1786.

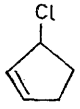
treatment with thionyl chloride–ether gave mainly *endo*-chloride (1) with retention, whereas phosphorus pentachloride gave more of the *exo*-chloride (2).[8] In both cases,



(1) X = Cl; Y = H
(2) X = H; Y = Cl
(3) X,Y = : O
(4) X = OH; Y = H
(5) X = H; Y = OH
(6) X,Y = : NOH
(7) X = NH_2 ; Y = H
(8) X = H; Y = NH_2
(9) X = H; Y = N_3
(10) X = O-p-NB; Y = H



(11) X = Cl
(12) X = OH
(13) X = NH_2



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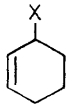
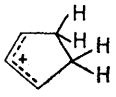


(15) X = Cl
(16) X = OH



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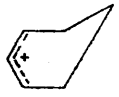

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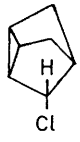

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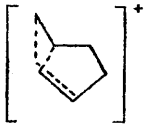


(20)

the homoallylic product, 4-chlorocyclohexene (11), and traces of 3-chlorocyclohexene (15) were also formed.

solution. The rearrangement, probably *via* a tight ion-pair, resembles that of the cyclobutane analogue 5-*endo*-tosyloxybicyclo[2.1.1]hexane.[9] Preparative g.l.c. gave pure *endo*-chloride (1), but the fraction containing *exo*-chloride (2) was contaminated with 4-chlorocyclohexene, and was further purified by selective bromination of the olefinic impurity followed by distillation.

Each chloride was solvolysed in 70% aqueous acetone and the alcoholic products were analysed by n.m.r. and g.l.c. Calcium carbonate was used to take up hydrochloric acid as otherwise the bicyclic alcohols (4) and (5) first formed were isomerised to cyclohex-3-enol[10] (12). The results are in Table 1.

Deamination offered an alternative route to the 2-bicyclohexyl cation. Lithium aluminium hydride reduction of 2-hydroxyiminobicyclohexane (6) gave largely 2-*endo*-aminobicyclo[3.1.0]hexane (7) (93%), as did sodium–ethanol as reducing agent. The *exo*-amine (8) was prepared *via* the epimeric 2-chloro-compounds which afforded the 2-azides, separated by g.l.c. at 68°. The 2-*exo*-azide (9) when reduced with lithium aluminium hydride gave the 2-*exo*-amine. In all this work the identification of 2-*endo*- and 2-*exo*-derivatives was easily made from the characteristic n.m.r. signals for 2-H which appeared as a doublet (*J ca.* 7 Hz) for *exo*-compounds and as a complex multiplet at lower field for *endo*-compounds (no shielding by the cyclopropane ring).[10]

These amines on treatment with sodium nitrite in buffered aqueous solution also gave the bicyclic alcohols (4) and (5) and cyclohex-3-enol (12) (Table 1). Alternatively, deamination of 4-aminocyclohexene (13) again gave the epimeric bicyclohexan-2-ols,[11] by the expected homoallylic rearrangement to the 2-bicyclo[3.1.0]hexyl cation. Here, unlike the deamination of the bicyclic amines (7) and (8), formation of tars indicated side reactions, however, and the formation of cyclohex-2-enol showed that a [1,2] hydride shift leading to the allylic cation was competing with homoallylic rearrangement.

A near constant ratio of *endo*- and *exo*-bicyclic alcohols (4) and (5) was observed (Table 1), whether from *endo*- or *exo*-precursors in the bicyclic series, whether by deamination or solvolysis; the same ratio is found in products of 4-aminocyclohexene. This evidence sup-

TABLE 1
Analysis of products from solvolysis and deaminations

Starting product	Total yield of alcohols (%)	Product ratio *endo*-ol (4)	*exo*-ol (5)	Cyclohex-3-enol	*exo*-Epimer in bicyclic alcohols (%)
endo-2-Chlorobicyclohexane (1)	66	28 (32) [a]	60 (55) [a]	12 (13) [a]	68
exo-2-Chlorobicyclohexane (2)	41	36 (36) [a]	52 (50) [a]	12 (14) [a]	59
endo-2-Aminobicyclohexane (7)	65	31	53	16	63
exo-2-Aminobicyclohexane (8)	35 [b]	32·5	50·5	17	61
4-Aminocyclohexene (13)	20 [c]	18	25	38	58

[a] Product ratio after further 100 h under solvolysis conditions. [b] Low yield due to increased olefinic product. [c] Product includes 19% cyclohex-2-enol.

The neat bicyclic chlorides had isomerised mainly to 4-chlorocyclohexene after two weeks at 20°, but they could be stored satisfactorily at −40° or in benzene

[8] P. K. Freeman, F. A. Raymond, and M. F. Grostic, *J. Org. Chem.*, 1967, **32**, 24.
[9] K. Wiberg, B. R. Lowry, and T. H. Colby, *J. Amer. Chem. Soc.*, 1961, **83**, 3998.
[10] The methoxy-derivatives are also isomerised with acid, see P. K. Freeman, M. F. Grostic, and F. A. Raymond, *J. Org. Chem.*, 1965, **30**, 771.
[11] The same deamination, but in acetic acid, has been reported, M. Hanack and W. Keberle, *Chem. Ber.*, 1963, **96**, 2937.

ports an S_N1 process in solvolysis of the chlorides. The *exo*-chloride (2) gives an *endo* : *exo* ratio of alcohols closer to that found in deamination than does *endo*-chloride (1). In solvolysis, but not in deamination, tight and solvent separated ion-pairs are the expected intermediates.[12] For *exo*-chloride (2) easy access of solvent to the *exo*-face should rapidly convert the tight ion-pair to a solvent separated ion-pair, particularly as the 2-cation is relatively stable. For the *endo*-chloride (1), the tight ion-pair is held on the more hindered *endo*-face of the bicyclo[3.1.0]hexyl system and here direct solvent attack from the *exo*-face will compete with the sterically hindered process giving solvent separated ion-pairs. This accounts for the greater proportion of inverted product from *endo*-chloride (1) and the minor deviation from the *endo* : *exo* ratio found in the other cases. Further evidence for ion-pairs in solvolysis is reported below.

The fairly constant proportion of cyclohex-3-enol (12) from bicyclic precursors is strong evidence that the intermediate 2-bicyclohexyl cation is non-classical with positive character at C-5. None of the alternative homallylic rearrangement product cyclopent-2-enylcarbinol, nor any cyclobutanols, bicyclo[2.2.0]hexan-2-ol * or bicyclo[2.1.1]hexan-5-ol, was detected. The latter observation suggests that bicyclobutonium type delocalisation involving interaction of C-2 with C-5 and -6 is not very important here.[13]

Rate Studies.—Solvolysis rates of the bicyclic chlorides (1) and (2) were measured conductometrically at 25° in 70% acetone. About 10% less than the theoretical hydrochloric acid was formed, owing to a competing reaction, the rearrangement of the ion pairs to isomeric, but less reactive, chlorides. Taking account of this led to satisfactory first-order plots. Rate constants (Table 2) for the two chlorides were very similar: $k_{endo} : k_{exo} = 1{\cdot}52$, the ratio being very close to that since reported for 4-nitrobenzoates (*p*-NB) [14] and for 4-oxopyridinium [15] derivatives within the same system. The composition of non-solvolysed chlorides after one half-life showed that there was slight interconversion of *endo*- and *exo*-chlorides by internal return, but not enough to affect the rate constants; the closeness of k_{endo} and k_{exo} was not due to equilibration of (1) and (2).

By comparison chlorocyclopentane in the same solvent system solvolysed much slower: the rate, too slow at 25°, was measured conveniently at 50°. The rate for bicyclic *endo*-chloride (1) extrapolated to 50° was *ca.* $5{\cdot}5 \times 10^4$ times faster ($\Delta\Delta G^{\ddagger}$ *ca.* 7 kcal mol^{-1}) showing that the cyclopropyl ring was giving the normal rate enhancing effect.

In order to compare the effect of the cyclopropyl group with that for a double bond, 3-chlorocyclopentene (14) was also solvolysed under similar conditions and proved remarkably reactive, so much so that measurable rates were only obtained at 0°. This rate (Table 2) was *ca.* 1350 times faster than that for *endo*-chloride (1) extrapolated to the same temperature ($\Delta\Delta G^{\ddagger}$ *ca.* 4 kcal mol^{-1}). This contrasted with simple allyl and cyclopropylcarbinyl systems where the latter normally solvolyse *ca.* 10 times faster.[16]

This marked reversal in the order of reactivity may be associated with a special stability of the cyclopent-2-enyl cation. 3-Chlorocyclohexene solvolyses at 25° at a considerably slower rate, and a rough comparison, assuming the solvolysis rate of allylic chloride (14) varies with temperature in the same way as bicyclic chloride (1), suggests that the rate is *ca.* 200—500 times faster for the five-membered allylic chloride than for the six-membered one at 25°. The 15—30 fold faster solvolysis of cyclopentyl derivatives compared with cyclohexyl derivatives in spite of unfavourable ring strain for the former is due to relief of ground state torsional strain.[17] For cyclopentenyl derivatives ground state torsional strain is less important due to the presence of two sp^2 hybridised carbon atoms [18] whilst in the planar cation (17) ring strain is more important (three sp^2 centres), and there is eclipsing of two methylene groups. The six-membered allyl cation (18) has less ring-strain and no eclipsed methylene groups nevertheless it is more difficult to form.†

In this connection, Deno has shown that alkyl-substituted cyclopentenyl cations are thermodynamically more stable than the corresponding cyclohexenyl cations

* Stereochemical considerations predict a *trans*-fused bicyclo[2.2.0]hexan-2-ol from the delocalised cation. The absence of such a strained product is not unexpected.

† To estimate ring strain generated by the formation of an sp^2 hybridised carbonium ion in a particular structure, Schleyer has used carbonyl stretching frequencies of the related ketone where the carbonyl group has replaced the cationic centre. In this way, differences in ring strain have been estimated in solvolysis of various tosylates and rates have been predicted.[17c] Use of carbonyl frequencies for the five- and six-membered saturated ring ketones predicts that on the grounds of ring-strain 3-chlorocyclohexene (15) should solvolyse $10^{0{\cdot}125(1745-1715)} = 10^{3{\cdot}75}$ times faster than 3-chlorocyclopentene (14). This is the minimum effect expected for one sp^2 hybridised centre and with extra strain produced by three such centres rate differences are expected to be even greater. Conjugated carbonyl frequencies have not been used as it is thought that the (suggested) special conjugative effect of the double bond in the five-membered ring allylic cation (18) will also be present in cyclopentenone. I.r. evidence supports this: introduction of a conjugated double bond into cyclopentanone lowers the carbonyl frequency by 40 cm^{-1}; the effect for cyclohexanone is a lowering of frequency by only 24 cm^{-1}.

With consideration of ring strain effects, the difference between the predicted and observed rates for chlorides (14) and (15) is, at a minimum, a factor of 10^6. We think this is far too large to be accounted for by torsional effects.

[12] S. Winstein, B. Appel, R. Baker, and A. Diaz, 'Organic Reaction Mechanisms,' Special Publication No. 19, The Chemical Society, London, 1965.

[13] For a discussion of various types of delocalisation in cyclopropylcarbinyl cations see P. von R. Schleyer and G. W. von Dine, *J. Amer. Chem. Soc.*, 1966, **88**, 2321, and also ref. 3*c*.

[14] Footnote [94], ref. 3*d*.

[15] G. H. Schmid and A. Brown, *Tetrahedron Letters*, 1968, 4695.

[16] J. D. Roberts and R. H. Major, *J. Amer. Chem. Soc.*, 1951, **73**, 2509; C. A. Bergstrom and S. Seigel, *ibid.*, 1952, **74**, 145.

[17] (*a*) H. C. Brown and G. Ham, *J. Amer. Chem. Soc.*, 1956, **78**, 2735; (*b*) L. Schotsmans, P. J. C. Fierens, and T. Vierlie, *Bull. Soc. chim. belges*, 1959, **68**, 580; (*c*) P. von R. Schleyer, *J. Amer. Chem. Soc.*, 1964, **86**, 1854.

[18] E. L. Eliel, N. L. Allinger, S. J. Angyal, and G. A. Morrison, 'Conformational Analysis,' Wiley-Interscience, New York, 1965, p. 202; R. Steyn and H. Z. Sable, *Tetrahedron*, 1971, **27**, 4429.

TABLE 2

Rates of solvolysis in 70% aqueous acetone

Compound	Temperature (°C)	$10^5k/s^{-1}$
endo-Chloride (1)	25	26·5
	10	3·94
exo-Chloride (2)	25	17·4
Chlorocyclopentane	50	0·008
3-Chlorocyclopentene (14)	0	5900
3-Chlorocyclohexene (15)	25	84
Nortricyclyl chloride (19)	50	0·0095
endo-O-*p*-NB (10)	100	0·523
5-Methyl-*endo*-ol (22) *p*-NB	100	10·8
5-Methyl-*exo*-ol (23) *p*-NB	100	6·4

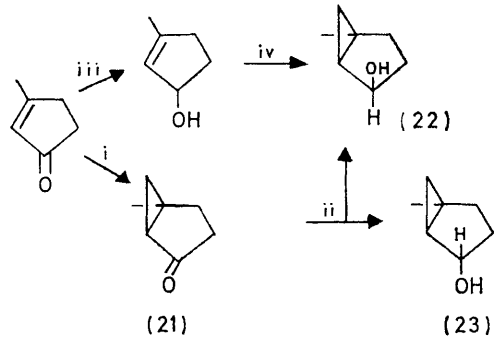
[a] Average of runs reported in Experimental section.

and under suitable conditions the latter may isomerise into the former.[19] Cyclopentenyl cations are also the end products of rearrangements and disproportionations of simpler cations.[20] The greater stability of the allyl cation (17) may be due to increased [1,3] π overlap when in a five-membered ring compared with the corresponding six-membered ring analogues.[21] The importance of [1,3] π overlap in the cyclobutenyl cation has been discussed by Katz [22] and in the open allyl cation by Olah.[23] Whatever the reason the same effect does not operate for the 2-bicyclohexyl cation.

The importance of ring strain on solvolysis rates is emphasized by the value for nortricyclyl chloride (19) at 50°. The extra bridging methylene group in (19) decreases the rate by 2×10^5 compared with that for (1) extrapolated to 50°. Estimation of ring strain effects from the appropriate carbonyl stretching frequencies (nortricyclone, 1762; bicyclohexan-2-one, 1720 cm^{-1}) predicts that at 25° (19) is solvolysed $10^{5\cdot2}$ times slower than (1).[17c]

As to the exact nature of the electron delocalisation in the 2-bicyclohexyl cation, assuming that the late transition state resembles the final cation, the small k_{endo} : k_{exo} ratio suggests that stabilisation is of the symmetrical homoallylic [13] type with both 1,5- and 1,6-bonds assisting ionisation for either *endo*- or *exo*-chloro-group as in (20). If the stabilisation were of the unsymmetrical homoallylic kind so that only the bond to the rear of the leaving group participated * the ratio should be higher than observed: k_{endo} would be influenced by the 1,5-bond which is alkyl-substituted and k_{exo} by the 1,6-bond which is not. Alkylation of simple cyclopropylcarbinol derivatives results in enhancement of solvolysis rates [13] by a factor *ca.* 10. Solvolysis rates of 5-methylbicyclo-[3.1.0]hexan-2-ol derivatives (below) confirmed the symmetric homoallylic stabilisation and ruled out the possibility that unsymmetrical homoallylic stabilisation was operating, with more subtle effects responsible for similarity of the rates for (1) and (2).

The 5-methylbicyclohexanols (22) and (23) were synthesised according to Scheme 1; *endo*-2-alcohol (22) was unambiguously synthesised by Simmons–Smith reaction on 3-methylcyclopent-2-enol [24] to confirm the relative stereochemistry of the epimeric alcohols from the Meerwein–Pondorf reduction of 5-methylbicyclohexanone (21). In anticipation of a more reactive series the less effective 4-nitrobenzoate leaving group was



SCHEME 1 Reagents: i, $Me_3\overset{+}{S}{=}OI^-$–NaH; ii, $Al(OPr^i)_3$–Pr^iOH; iii, $LiAlH_4$, −40°; iv, CH_2I_2–Zn–Cu

chosen in place of a chloro-group. The rates in 70% acetone at 100° were followed titrimetrically and compared with the 2-*endo*-4-nitrobenzoate (10) to determine the rate-enhancing effect of the 5-methyl group (Table 2). Little internal return was noted [4% for 5-methyl compounds and 8% for (10)]. Owing to the small quantities available, product analysis from the 5-methyl series was based only on n.m.r. spectra which showed 1-methylcyclohex-3-enol as the major product.

The 5-methyl-2-*endo*-4-nitrobenzoate was solvolysed 21 times faster than the 5-unsubstituted compound (10). Schleyer found a factor of 11 for a methyl group in the same position in the parent cyclopropylcarbinol 3,5-dinitrobenzoates.[13] Significantly, k_{endo} : k_{exo} for the 5-methyl series was 1·69, quite close to 1·52 obtained without the methyl group present. The 5-methyl group increases the rate of solvolysis of 2-*exo*-ester to almost the same extent as the *endo*-ester, therefore confirming the symmetric homoallylic delocalisation with both 1,5- and 1,6-bonds involved in a late transition state.

Attempts to repeat the study on the 6-*endo*-methyl

* We have previously used 'bishomoallylic' to imply delocalisation involving two bonds of cyclopropane [1] rather than 'symmetrical homoallyl' [4] or 'bisected form'.[13] 'Monohomoallyl' then corresponds to 'unsymmetrical homoallyl'. Whilst we prefer our original term to describe non-classical ions which strictly may be neither symmetrical nor bisected, a referee has pointed out that bishomoallylic has been used with the alternative meaning: delocalisation (symmetrical or otherwise) involving two cyclopropane groups. We therefore drop our original usage which had gained limited acceptance [5,6,15] and revert to the earlier nomenclature.

[19] N. C. Deno, J. Bollinger, N. Friedman, K. Hafer, J. D. Hodge, and J. J. Houser, *J. Amer. Chem. Soc.*, 1963, **85**, 2998; N. C. Deno and R. R. Lastominsky, *ibid.*, 1968, **90**, 4085.

[20] N. C. Deno, *Progr. Phys. Org. Chem.*, 1964, **2**, 140, 141; N. C. Deno, D. B. Boyd, J. D. Hodge, C. V. Pittman, and J. O. Turner, *J. Amer. Chem. Soc.*, 1964, **86**, 1744, 1745; H. G. Richey, 'Chemistry of Alkenes,' ed. J. Zabicky, Wiley-Interscience, New York, 1970, vol. 2, p. 65.

[21] T. S. Sorensen, *J. Amer. Chem. Soc.*, 1969, **91**, 6398.

[22] T. J. Katz and E. H. Gold, *J. Amer. Chem. Soc.*, 1964, **86**, 1600.

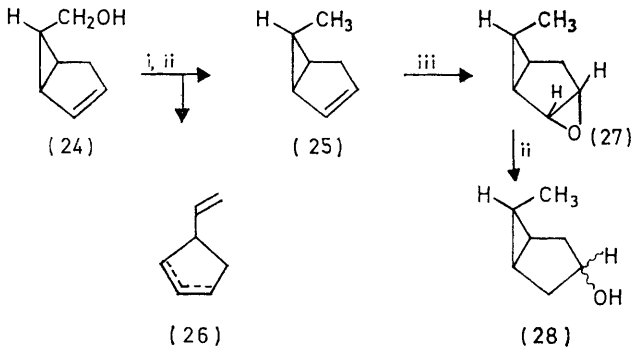
[23] G. A. Olah and M. B. Comisarow, *J. Amer. Chem. Soc.*, 1964, **86**, 5682.

[24] The hydroxyl group directs the methylene group to the same face, W. G. Dauben and G. H. Berezin, *J. Amer. Chem. Soc.*, 1963, **85**, 468.

series failed. Hydride reduction of the tosyl ester of the readily available [25] 6-*endo*-hydroxymethyl derivative (24) (Scheme 2) yielded vinylcyclopentenes (26; double bond isomers) as well as the desired 6-*endo*-methylbicyclo[3.1.0]hex-2-ene (25) which could be purified by g.l.c. The unwanted vinylcyclopentenes probably arise by homoallylic rearrangement of the initial ion pair from (24) involving the cyclopropylcarbinyl cation to the corresponding vinylcyclopentenyl cation prior to attack by the complex hydride.*

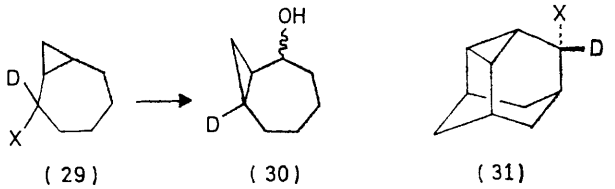
The 6-methylbicyclohexene (25) on treatment with peracetic acid gave the *exo*-epoxide (27) which was then reduced with lithium aluminium hydride. Unexpectedly, this gave a 3-alcohol (28) rather than the desired 2-alcohol as evidenced by the n.m.r. signal for the CHOH group in the product which appeared as a broadened triplet (identical coupling with *cis*-2- and -4-H). Direct S_N2 attack by hydride on the *endo*-face of epoxide (27) at C-2 appears very hindered. We suggest that the 3-alcohol is formed by initial complexing of the lithium ion with the oxide ring and ring-openiug to the stable 2-cation. Hydride transfer to C-2 by AlH_4^- from the *exo*-face would give the 3-*exo*-alcohol. Alternatively, an internal hydride shift of 3-H to C-2 would give the 3-ketone and thence, by attack of reagent from the least hindered face, the 3-*endo*-alcohol. The stereochemistry of the 3-alcohol was not established.. Owing to low yields in the formation of bicyclic olefin (25) the scheme was abandoned at this point.

The interconversion of one cyclopropylcarbinyl cation to other cyclopropylcarbinyl cations has been firmly established in the simple case by isotropic scrambling in labelled compounds.[2b] The three methylene groups



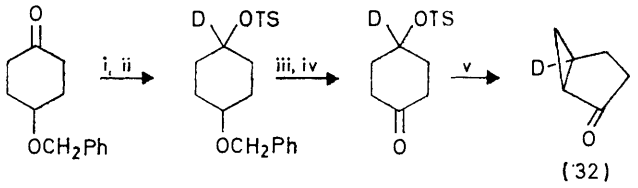
SCHEME 2 Reagents: i, TsCl–KOH–Et_2O; ii, $LiAlH_4$; iii, AcOOH

approach but do not reach full equivalence. Further examples are found in alkyl-substituted cyclopropylcarbinyl derivatives (see ref. 3*c*). Few examples have been reported in rigid systems however. Friederich and Wight reported [26] deuterium scrambling in solvolysis of 2-*exo*-bicyclo[5.1.0]octyl derivatives (29) ⟶ (30) but not in the 2-*endo*-derivatives. Baldwin, who detected similar scrambling in the dehydroadamantyl system (31) during solvolysis, argued that a tricyclobutonium ion may intervene, but as a transition state rather than a stable



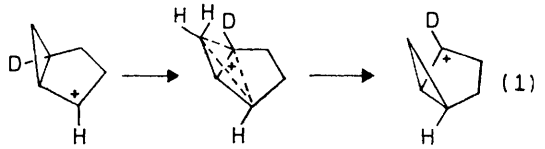
intermediate.[27] The thermal [1,3] shift probably involves inversion at the migrating centre.

We have synthesised 5-deuteriobicyclohexanone (32) by the route outlined in Scheme 3 in order to test for



SCHEME 3 Reagents: i, $LiAlD_4$; ii, $TsCl–C_5H_5N$; iii, $Pd–H_2$; iv, $HCrO_4$; v, $NaH–[CH_2]_4O$

similar rearrangement in the deuteriated 2-cation, *i.e.* reaction (1). The ketone (32) was subjected to the



following sequence of reactions: reduction to the epimeric alcohols, then conversion to the corresponding chlorides, solvolysis back to the bicyclohexanols (with some cyclohex-3-enol) and finally oxidation back to bicyclohexanone (32). If any rearrangement (1) occurred, either in formation of the chlorides or in solvolysis, the final oxidation step would lead to loss of deuterium. Comparison of the mass spectra of the initial and cycled bicyclohexanone, after purification, showed $<1\%$ loss of deuterium. We conclude that the rearrangement does not occur to any significant extent with the 2-bicyclo[3.1.0]hexyl cation in the strongly nucleophilic aqueous acetone.

EXPERIMENTAL

N.m.r. spectra were obtained at 60 MHz on a Varian A60 spectrometer, and i.r. spectra on a Unicam SP 200 machine. Analytical g.l.c. involved a Perkin-Elmer F11 instrument with a 200 ft glass capillary column coated with didodecyl phthalate, and preparative g.l.c. was carried out on an A700 Aerograph machine with 10 ft × $\frac{3}{8}$ in columns of 15% Carbowax unless otherwise stated. Kieselgel G (Merck) was used for chromatography. Organic extracts were normally dried with sodium sulphate.

* An alternative explanation would involve hydride attack on a non-classical cation.

[25] M. Rey and A. S. Dreiding, *Helv. Chim. Acta*, 1965, **48**, 1985.

[26] L. E. Friederich and F. R. Wight, *J. Amer. Chem. Soc.*, 1970, **92**, 1807.

[27] J. E. Baldwin and W. D. Fogelsong, *J. Amer. Chem. Soc.*, 1968, **80**, 4303, 4311.

2-*Chlorobicyclo*[3.1.0]*hexanes* (1) *and* (2).—(a) *endo*-Bicyclo[3.1.0]hexan-2-ol (4·1 g) (7% *exo*-epimer) in ether (50 ml) was treated with phosphorus pentachloride until no further gas evolution was noted and solid reagent was present. The ether was decanted into ice–water, shaken, then washed with sodium hydrogen carbonate solution, and dried. Removal of the ether gave the crude chlorides which were distilled (bulb-to-bulb) at 60° and 15 mmHg as an oil (2·4 g, 48%). G.l.c. analysis at 83° by passage through the metal injection block at 80° or at room temperature resulted in isomerisation mainly to 4-chlorocyclohexene. Direct injection of a dilute solution in benzene (0·5 ml) on to the column at 80° after passage of diethylamine (trace) avoided this isomerisation, and gave four peaks with R_t and areas shown: *exo*-2-chloride (2) (13·5 min, 55%), 4-chlorocyclohexene (11) (13·7 min, 12%), *endo*-2-chloride (1) (14·7 min, 33%), and 3-chlorocyclohexene (15) (14·9 min, 1%). The first two peaks were not completely resolved. Identification was based on the retention times of authentic specimens and of known mixtures. N.m.r. analysis confirmed the g.l.c. results.

(b) *endo*-Bicyclohexan-2-ol (1·3 g; 7% *exo*-epimer) in ether (10 ml) at 0° was treated with thionyl chloride (excess).[8] After 24 h, work-up as above yielded the chlorides (0·85 g, 65%) which contained *exo*-2-chloride (2) (28·5%), 4-chlorocyclohexene (11) (12·5%), *endo*-2-chloride (1) (59%), and 3-chlorocyclohexene (15) (1%).

Preparative g.l.c. at 65° gave pure endo-2-*chlorobicyclo*[3.1.0]*hexane* (1) (Found: C, 61·75; H, 7·8. C_6H_9Cl requires C, 61·8; H, 7·7%) and the *exo*-2-chloro-derivative contaminated with 4-chlorocyclohexene (30%; n.m.r.). To the latter was added an amount of bromine in carbon tetrachloride sufficient to react with the olefinic component, and removal of carbon tetrachloride followed by careful bulb-to-bulb distillation of the residue gave a separation of the volatile bicyclic *exo*-chloride (2) from brominated material (<1% olefin by n.m.r. analysis).

2-*Azidobicyclo*[3.1.0]*hexanes*.—The crude bicyclic chlorides (1) and (2) (1·3 g, 0·011 mol), containing *ca.* 10% 4-chlorocyclohexene, were added to sodium azide (2·25 g, 0·04 mol) in dimethyl sulphoxide (28 ml)–water (2 ml) and the mixture was heated on a steam-bath for 1·5 h. After addition of water, ether extraction gave the crude azides. Rapid filtration through a silica column (benzene as eluant) removed polar impurities and the products (68%) were shown to contain *exo*- and *endo*-2-azides (64 : 34), with 3-azidocyclohexene (2%) as impurity by g.l.c. (5 ft dinonyl phthalate column, 77°, R_t 24, 33, and 29 min). Preparative g.l.c. at 68° gave the 2-endo-*azide* (Found: C, 58·95; H, 7·4; N, 33·6. $C_6H_9N_3$ requires C, 58·3; H, 7·4; N, 34·1%); δ 3·95 (1H, m, 2-H) and 0·8—0·2 (2H, m, cyclopropyl CH_2), and the 2-exo-*azide* (9) (Found: C, 58·55; H, 7·15; N, 33·85%), δ 3·7 (1H, d, 2-H) and 0·8—0·2 (2H, m, cyclopropyl CH_2).

2-endo-*Aminobicyclo*[3.1.0]*hexane* (7).—Bicyclo[3.1.0]-hexan-2-one (6 g, 0·063 mol) with hydroxylamine hydrochloride (6·7 g, 0·096 mol) in aqueous sodium acetate gave the 2-*oxime* (6) (5·6 g, 80%) as an oil, b.p. 78° at 0·8 mmHg, which slowly crystallised, m.p. 34—36° (Found: C, 64·9; H, 8·35; N, 12·3. C_6H_9NO requires C, 64·9; H, 8·2; N, 12·6%). The O-*tosylate* prepared from tosyl chloride–pyridine, proved unusually stable and was crystallised from absolute ethanol–light petroleum (b.p. 60—80°), m.p. 116—117° (Found: C, 58·6; H, 5·65. $C_{13}H_{15}NO_3S$ requires C, 58·8; H, 5·7%). The 2-hydroxyiminobicyclohexane (11·1 g, 0·1 mol) in ether (100 ml) was added to stirred lithium aluminium hydride (6·0 g, 0·15 mol) in ether (20 ml) at 0°. After a further 6 h, cautious addition of a limited amount of water to destroy the excess of hydride, followed by filtration gave an ether solution of the *exo*- and *endo*-2-amino-derivatives (ratio 7 : 93 by g.l.c. analysis; 4 ft column of 5% 1-hydroxyethyl-2-heptadecenylimidazolidine) which was dried (Na_2SO_4, then $CaSO_4$) and treated with an excess of hydrogen chloride. The precipitated amine hydrochlorides were filtered off, washed with dry ethyl acetate, and crystallised from chloroform–ethyl acetate to give the 2-endo-*amine hydrochloride* (2·1 g, 29%), m.p. 215° (Found: C, 53·55; H, 8·95; N, 10·5. $C_6H_{12}ClN$ requires C, 53·9; H, 9·0; N, 10·5%). The *benzamide* derivative was crystallised from benzene–hexane, m.p. 155° (Found: C, 77·6; H, 7·65; N, 6·95. $C_{13}H_{15}NO$ requires C, 77·6; H, 7·5; N, 6·95%).

2-exo-*Aminobicyclo*[3.1.0]*hexane* (8).—*exo*-2-Azidobicyclohexane (620 mg) in ether was treated with lithium aluminium hydride (190 mg; excess) for 10 h. Work-up as above gave the 2-exo-*amine hydrochloride* from chloroform, m.p. 178—179° (0·5 g, 74%) (Found: C, 54·15; H, 8·75; N, 10·8%). The *benzamide* had m.p. 164° (Found: C, 77·2; H, 7·35%).

4-*Aminocyclohexene* [11] (13).—(a) *Azide route*. 4-Tosyloxycyclohexene [11] (15 g, 0·06 mol) in dimethyl sulphoxide (100 ml) was added to sodium azide (16 g, 0·24 mol) in dimethyl sulphoxide (200 ml) and water (60 ml) heated to 70°. After 1 h at this temperature the mixture was cooled, diluted with water (300 ml), and extracted with ether to give the crude azide, $\nu_{max.}$ 2150 cm^{-1}, no cyclopropyl signal in n.m.r. spectrum. Addition of the crude azide in dry ether (50 ml) to lithium aluminium hydride (3·0 g; excess) in ether at such a rate as to maintain a gentle reflux followed by work-up in the usual way gave 4-aminocyclohexene hydrochloride (3·0 g, 38%) from chloroform–ethyl acetate, m.p. 182° (Found: C, 54·2; H, 9·2%).

(b) *Gabriel method*. 4-Tosyloxycyclohexene [11] (20 g, 0·08 mol) was added to potassium phthalimide (16 g, 0·086 mol) in dimethylformamide (320 ml) and the mixture was boiled for 10 min, before addition of water and extraction with chloroform. The extracts after washing with dilute sodium hydroxide and water gave 4-*phthalimidocyclohexene*, m.p. 175° (from aqueous ethanol) (2·3 g, 0·01 mol, 15%) (Found: C, 73·6; H, 5·6. $C_{14}H_{13}NO_2$ requires C, 73·9; H, 5·8%). This was heated under reflux with hydrazine hydrate (80%, 2·6 ml, 0·026 mol) in methanol (50 ml) for 1 h. Water (25 ml) was added, methanol was distilled off, and the suspension was heated with concentrated hydrochloric acid (7 ml) for 20 min. Phthalhydrazide was filtered off, and the filtrates after basification were extracted with ether. The usual work-up gave the amine hydrochloride, m.p. 182° (0·76 g, 46%).

Nitrous Acid Deaminations.—(a) *endo*-2-Aminobicyclo-[3.1.0]hexane hydrochloride (3·3 g, 0·0248 mol) and potassium dihydrogen phosphate (3·367 g, 0·0248 mol) in water (35 ml) at 0° were treated with sodium nitrite (1·078 g, 0·0248 mol). After 2 h at 0° and 48 h at ambient temperature the solution was saturated with sodium chloride and extracted with ether. After washing with saturated sodium hydrogen carbonate solution and brine the ether yielded the alcohols, purified by distillation (1·3 g, 59%).

(b) *exo*-2-Aminobicyclo[3.1.0]hexane hydrochloride (0·36 g, 0·0027 mol) when treated in the same way gave 0·076 g of distilled alcohols (35%).

(c) 4-Aminocyclohexene hydrochloride (2·67 g, 0·20 mol), when treated as above, gave an insoluble tarry product and the crude distilled alcohols (0·4 g, 20%) left a dark brown residue unlike the earlier deaminations.

Analysis of the Alcohols.—N.m.r. analysis of the crude alcohol mixtures showed the presence of olefinic material other than olefinic alcohols, but this was largely removed by distillation. G.l.c. analysis (83°) of the distilled alcohols showed the presence of *exo*- and *endo*-bicyclo[3.1.0]hexan-2-ols (5) and (4) and cyclohex-3-enol (12) as judged by the analysis of known mixtures. N.m.r. analysis confirmed the g.l.c. results, and indicated the presence of small amounts (1—2%) of cyclohex-2-enol (16) which was not resolved from *exo*-2-alcohol (5) by g.l.c. analysis. The results are in Table 1.

Products from Solvolysis of the Bicyclic Chlorides.—*endo*-2-Chlorobicyclo[3.1.0]hexane (0·02 g) in 70% aqueous acetone (3 ml) containing finely ground calcium carbonate (0·1 g) was left for 20 h at ambient temperature and a sample was analysed for alcohols. Ether extraction after 120 h then gave the alcohols (0·012 g, 66%) which were analysed as before. This further reaction time did not alter the ratio of alcohols. Earlier experiments with *endo*-chloride in *refluxing* 70% acetone without removal of hydrochloric acid gave only cyclohex-3-enol.

4-Chlorocyclohexene was unaffected by the conditions used for solvolysis of bicyclic chlorides, hence in the determination of alcohols produced from *exo*-chloride, a sample contaminated with 30% of 4-chlorocyclohexene was solvolysed and the alcohols analysed as before (Table 1).

3-*Chlorotricyclo*[2.2.1.$0^{2,6}$]*heptane* (19).—Hydrogen chloride was bubbled through bicyclo[2.2.1]hepta-2,5-diene (20 g) until the increase in weight corresponded to the uptake of 1 mol. N.m.r. analysis on the distilled chlorides indicated only 24% of tricyclic chloride the remainder being 2-chlorobicyclo[2.2.1]hept-5-ene. After heating of the mixture in carbon tetrachloride (100 ml) with zinc chloride (*ca.* 0·5 g) for 12 h, followed by removal of the catalyst, distillation of the equilibrated chlorides gave material (17·5 g, 63%), b.p. 74—76° at 40 mmHg, now containing 78% of tricyclic chloride. Preparative g.l.c. gave pure 3-chlorotricyclo-[2.2.1.$0^{2,6}$]heptane.

3-*Chlorocyclopentene.*—Hydrogen chloride was bubbled into cyclopentadiene at 0° until the theoretical weight of hydrogen chloride had been taken up. The allylic chloride had b.p. 55° at 90 mmHg, but polymerised and darkened, slowly at room temperature, rapidly when warm; it was stored at −40°. Just prior to use, samples were redistilled, and a solution in ether was washed at 0° to remove traces of hydrogen chloride, rapidly dried, and the ether removed at 0°.

3- *and* 4-*Chlorocyclohexenes.*—A mixture of cyclohex-2-enol (16) and -3-enol (12) [28] (30 : 70) (1 g) in ether (50 ml) at 0° was treated with phosphorus pentachloride in the same way as for the bicyclic chlorides and gave, upon distillation, the 3- and 4-chlorocyclohexenes (0·59 g, 53%). G.l.c. analysis showed them to be in a ratio of 35 : 65. The n.m.r. spectrum included signals for the 3-chloro-compound at δ 5·6 (m, olefinic) and 4·3—4·7 (m, CHCl) and for the 4-chloro-derivative at 5·8 (m, olefinic) and 3·9—4·3 (m, CHCl). Integration of the olefinic region gave the ratio as 36 : 64. This mixture was used for solvolysis studies.

Rate Studies.—In a typical experiment, aqueous acetone (70% v/v; 50 ml) was pipetted out and kept at 25° in a thermostatted bath, and a sample of *endo*-chloride (1) (*ca.* 20 mg) accurately weighed in a short glass capillary (2 mm diam.) open at both ends was added. The mixture was well shaken immediately and the timing started. A sample (10 ml) was pipetted into the conductivity cell in the same bath and the conductivity was measured at regular intervals over 3 h. After not less than 24 h an ' infinity ' reading was taken. Total acid formed was estimated by titration of aliquot portions with 0·02N-NaOH.

The cell was calibrated by introduction by an Agla micrometer syringe of successive 0·1 μl samples of 2N-HCl into an accurate volume (10 ml) of the 70% acetone, and measurement of the change in conductivity. Straight line plots were obtained at 10, 25, and 50°.

endo-2-*Chlorobicyclo*[3.1.0]*hexane* (1). At 25 or 10° this chloride solvolysed to give only 87·5 ± 1% of the theoretical hydrochloric acid (measured by titration or conductivity). Good first-order plots were obtained and the specific rate constant was derived graphically from expression (2).

$$kt = \ln \frac{[RCl]}{[RCl] - [HCl]/0{\cdot}875} \qquad (2)$$

Values of 10^4k found were: 25°; 2·67 ± 0·05, 2·72 ± 0·03, 2·61 ± 0·06, and 2·68 ± 0·05 s^{-1}: 10°; 0·392 ± 0·006 and 0·395 ± 0·008 s^{-1}.

exo-2-*Chlorobicyclo*[3.1.0]*hexane* (2). Good first-order plots were obtained, either with the pure chloride or with 4-chlorocyclohexene as contaminant; 90 ± 1% of the theoretical hydrochloric acid was generated. With impure chloride it was found convenient to take the concentration of hydrochloric acid at ' infinity ' as directly proportional to the concentration of active chloride and a modified rate expression (3) was used. Values of 10^4k at 25° were: 1·73 ± 0·04, 1·69 ± 0·05, 1·76 ± 0·03, and 1·77 ± 0·05 s^{-1}.

$$kt = \ln \frac{[HCl]_\infty}{[HCl]_\infty - [HCl]} \qquad (3)$$

Chlorocyclopentane. AnalaR grade chlorocyclopentane was redistilled before use. After 150 h at 50° only 2% of the theoretical hydrochloric acid had been formed in solvolysis. The rate was followed for only 5% reaction and an approximate specific rate constant of 8 ± 1 × 10^{-8} s^{-1} was obtained graphically.

3-*Chlorocyclopentene.* The solvolysis rate was too fast to be conveniently measured at 25° and runs were made at 0°, using conductance readings as a direct measure of the progress of reaction, and the final reading as directly proportional to the initial concentration of chlorocyclopentene. 10^2k at 0°: 5·6 ± 0·2, 5·5 ± 0·2, 6·0 ± 0·4, and 5·7 ± 0·2 s^{-1}.

3-*Chlorocyclohexene* (15). Impure samples contaminated with 64% of the homoallylic chloride (11) gave values of 10^4k at 25° of 8·2 ± 0·3 and 8·5 ± 0·4 s^{-1} with good first-order plots.

3-*Chlorotricyclo*[2.2.1.$0^{2,6}$]*heptane* (19). Because of low reactivity, the solvolysis rate was measured at 50° and values of 10^8k of 9·6 ± 0·1 and 9·3 ± 0·2 s^{-1} were obtained.

Isomerisation of Bicyclic Chlorides by Ion-pair Return in Solvolysis.—*endo*-2-Chlorobicyclohexane (1) (0·35 g) in aqueous acetone (10 ml) was solvolysed for 45 min (1 half-life) and after dilution with water the mixture was immediately extracted with pentane. Combined g.l.c. and n.m.r. analysis of this extract showed the major components

[28] J. B. Senderens, *Compt. rend.*, 1937, **180**, 791.

of the recovered chloride to be 85% *endo*-2-chloride, 10% *exo*-2-chloride, and 5% 4-chlorocyclohexene (error ± 1%).

Similarly *exo*-2-chlorobicyclohexane (2) (0·08 g) solvolysed for one half-life (1 h) showed 6% of *endo*-chloride and some 4-chlorocyclohexene.

When *exo*- and *endo*-chlorides were solvolysed for 48 h for complete reaction, pentane extraction of unsaponified residues gave at least nine partially resolved peaks (of which a major one was 4-chlorocyclohexene) by g.l.c. analysis with the retention times expected for C_6-chlorides. The two chlorides gave slightly different product ratios.

3-*Methylcyclopent*-2-*enol*.—Lithium aluminium hydride (0·23 g, 0·005 mol) in ether (10 ml) was added to stirred solution of 3-methylcyclopent-2-enone [29] (2 g, 0·02 mol) in ether (20 ml) at −40°. After addition, the solution was allowed to warm to 20° over 2 h, and work-up using sodium potassium tartrate in the usual manner gave crude 3-methylcyclopent-2-enol (1·4 g, 70%), $\nu_{max.}$ 3480 and 1665 cm^{-1}, δ 5·4—5·6 (1H, m, olefinic H) 4·6—4·9 (1H, m, CHOH), 2·1 (s, OH), 1·8 (3H, s, Me), and 2·6—2·0 (remainder). N.m.r. signals in the region δ 0·8—1·4 indicated the presence of some 3-methylcyclopentanol as impurity, confirmed by t.l.c. (In sodium borohydride reductions the saturated alcohol was the major product.) Zinc–copper couple (1 g) and di-iodomethane (2·7 g, 0·01 mol) were stirred and heated under reflux in ether (100 ml) for 1 h. Crude 3-methylcyclopent-2-enol (1 g, 0·01 mol) was added and heating was continued with stirring for 16 h. The ether layer, after washing with saturated ammonium chloride gave an oil (2 g), chromatographed with 5% ethyl acetate–chloroform as eluant. 5-Methylbicyclo[3.1.0]hexan-*endo*-2-ol was eluted first (0·4 g, 35%) $\nu_{max.}$ 3400 cm^{-1}, δ 4·8—4·3 (1H, m, CHOH), 2·1 (s, OH), 2·0—1·4 (5H, m, cyclopentane ring protons), 1·2 (3H, s, Me), and 0·1—0·9 p.p.m. (2H, m, cyclopropane CH_2). The alcohol showed only one peak by g.l.c. and was characterised as the 4-*nitrobenzoate*, m.p. 85—88° (from methylcyclohexane) (Found: C, 64·1; H, 5·85; N, 5·65. $C_{14}H_{15}NO_4$ requires C, 64·4; H, 5·75; N, 5·35%).

5-*Methylbicyclo*[3.1.0]*hexan*-2-*one*.—Trimethylsulphoxonium iodide (2·2 g, 0·01 mol) was added all at once with stirring to sodium hydride (0·24 g, 0·01 mol) in dry dimethylformamide (25 ml). Evolution of hydrogen ceased after 10 min and 3-methylcyclopent-2-enone (1 g, 0·01 mol) was added at once. After 1 h, dichloromethane (50 ml), then water (50 ml) was added. The usual work-up and chromatography with 1% ethanol–chloroform as eluant gave the ketone (0·475 g, 41%) $\nu_{max.}$ 1730 cm^{-1}, δ 2·4—1·5 (5H, m, cyclopentane ring protons), 1·35 (3H, s, Me), and 1·3—1·0 (2H, m, cyclopropyl CH_2), 1 peak by g.l.c. The 2,4-*dinitrophenylhydrazone*, had m.p. 153—154° (from aqueous methanol) (Found: C, 53·25; H, 4·8; N, 19·1. $C_{13}H_{14}N_4O_4$ requires C, 53·3; H, 4·8; N, 19·3%). The *semicarbazone* crystallised from aqueous ethanol, then methylcyclohexane, m.p. 145—146° (Found: C, 57·15; H, 7·65; N, 24·8. $C_8H_{13}N_3O$ requires C, 57·45; H, 7·8; N, 25·1%).

Meerwein–Pondorf Reduction of 5-*Methylbicyclo*[3.1.0]-*hexan*-2-*one*.—The 5-methylbicyclohexanone (2·0 g, 0·018 mol) and freshly distilled aluminium isopropoxide (8·4 g, 0·041 mol) were dissolved in dry isopropyl alcohol (100 ml) and the mixture distilled very slowly through a fractionating column so that the distillate came over between 60 and 80°. After 5 h the distillate gave a negative test for acetone (2,4-dinitrophenylhydrazine). A saturated solution of sodium potassium tartrate, sufficient to dissolve all aluminium salts, was added, the organic phase was separated, and the aqueous layer was extracted with ether (3 × 50 ml). The combined organic extracts were washed with brine, dried, and distilled to remove most of the isopropyl alcohol. The residue on bulb-to-bulb distillation gave 1·8 g (90%) of crude alcohols, b.p. 100° at 10 mmHg. G.l.c. analysis showed the *endo*- and *exo*-alcohols to be in ratio 61 : 39 (R_t 15·6 and 14·2 min respectively), and they were separated by preparative g.l.c. The *endo*-alcohol was identical with the sample prepared by the Simmons–Smith reaction (above) whilst the *exo*-alcohol was characterised as the 4-*nitrobenzoate*, m.p. 53—54·5° (from methylcyclohexane) (Found: C, 64·9; H, 5·75; N, 5·65. $C_{14}H_{15}NO_4$ requires C, 64·4; H, 5·75; N, 5·4%).

Solvolysis Rates of 4-*Nitrobenzoate Esters*.—Samples of the esters were recrystallised just before use and their m.p.s checked as a criterion of purity. Solvolysis was in sealed ampoules at 100 ± 0·1° in 70% aqueous acetone. 4-Nitrobenzoic acid was estimated titrimetrically with Bromothymol Blue as indicator against 0·1N-NaOH over a period of *ca.* five half-lives. The last determination was run for a considerably longer time and the ' infinity ' titre taken (to determine the amount of internal return). Use of 80% aqueous dioxan as an alternative solvent was not satisfactory: apparent rates of solvolysis increased after several hours due possible to oxidation of the solvent.

Results for 2-endo-*bicyclo*[3.1.0]*hexyl* 4-*nitrobenzoate*. Initial concentration $8·695 \times 10^{-3}$M. Infinity titre $8·007 \times 10^{-3}$. Internal return factor 7·9%. Specific rate constant at 100° $10^6k = 5·25 \pm 0·2$ and $5·20 \pm 0·25$ s^{-1}.

5-*Methylbicyclo*[3.1.0]*hexan*-2-endo-*ol*. Internal return factor 3·9%. At 100° $10^5k = 10·9 \pm 0·2$, $10·5 \pm 0·4$, $11·0 \pm 0·2$, and $10·7 \pm 0·2$ s^{-1}.

5-*Methylbicyclohexan*-2-exo-*ol*. Internal return factor 4·9%. At 100° $10^5k = 6·4 \pm 0·8$, $6·8 \pm 0·7$, $6·3 \pm 0·3$, and $6·1 \pm 0·1$ s^{-1}.

Product Analysis.—5-Methyl-2-*endo*-bicyclo[3.1.0]hexyl 4-nitrobenzoate (0·04 g) was solvolysed as above for 24 h. Extraction with pentane yielded a pale yellow liquid (0·017 g, 95%) giving only one peak by g.l.c. analysis whose n.m.r. spectrum was in agreement with that expected for 1-methylcyclohex-3-enol, δ 5·55—5·75 (2H, m, olefinic), 2·4—2·0 (4H, m, allylic), 1·6—1·8 (2H, m, remaining ring protons), 1·7 (1H, s, OH), and 1·25 (3H, s, Me). The spectrum showed small signals in the aromatic region due to traces of 4-nitrobenzoate ester (or esters?) formed by internal return. Further characterisation was not attempted.

endo-6-*Methylbicyclo*[3.1.0]*hex*-2-*ene*.—Bicyclo[3.1.0]hex-2-ene-6-*endo*-carbaldehyde [30] (5 g, 0·046 mol) in ether (50 ml) was added to lithium aluminium hydride (0·7 g, 0·018 mol) in ether (50 ml). Work-up in the usual manner with sodium potassium tartrate gave crude *endo*-6-hydroxymethylbicyclo[3.1.0]hex-2-ene, b.p. 85—87° at 25 mmHg (4·0 g, 79%). The 6-hydroxymethyl derivative (6·0 g, 0·054 mol) and tosyl chloride (10·3 g, 0·054 mol) in ether (200 ml) were stirred rapidly below −5° whilst powdered potassium hydroxide (8·4 g, 0·15 mol) was added in small amounts. After 3 h at −5° the mixture was poured onto crushed ice and the ether layer was thoroughly dried (Na_2SO_4, then $CaSO_4$). The ether solution was concentrated, then immediately added dropwise to lithium aluminium hydride (3·0 g, 0·079 mol) in ether (50 ml) at −10°. After 3 h,

[29] R. Acheson and R. Robinson, *J. Chem. Soc.*, 1952, 1127.
[30] J. Meinwald, S. S. Labana, and M. S. Chadha, *J. Amer. Chem. Soc.*, 1963, **85**, 582.

work-up as above gave an ether solution of hydrocarbons: g.l.c. analysis (83°) showed two peaks with R_t 5·1 and 6·0 min (relative areas 2 : 1). Preparative g.l.c. (Carbowax) gave the two products; the first, trapped by solution in carbon tetrachloride, had the characteristic smell of a diene and was only characterised by its n.m.r. spectrum which showed complex absorptions at δ 5·4—6·2 and 5·1—4·7 (olefinic protons) and 2·9—1·5 (cyclopentane CH) in an approximate ratio of 1 : 1. It was considered to be a mixture of 3- and 4-vinylcyclopentenes. The second component, 6-endo-*methylbicyclo*[3.1.0]*hex*-2-*ene*, was isolated as an oil (0·5 g, 9·6%) (Found: C, 89·3; H, 10·9. C_7H_{10} requires C, 89·3; H, 10·7%), δ 5·5—5·7 (2H, m, olefinic), 0·7—0·85 (3H, d, Me), and 0·85—2·5 (5H, m, remainder).

endo-6-*Methylbicyclo*[3.1.0]*hexan*-3-*ol*.— Peracetic acid (31%, 1·3 g, 5 mmol) was added dropwise to an ice-cooled stirred suspension of finely divided sodium carbonate (1·5 g, 12 mmol) in dichloromethane (50 ml) containing the *endo*-6-methylbicyclohexene. After a further 1 h solid material was filtered off and washed (CH_2Cl_2). The filtrate and washings on distillation gave the crude epoxide (0·21 g, 71%). G.l.c. indicated 4% impurity with lesser R_t (9·5 min) than the epoxide (11·9 min), $\nu_{max.}$ 1220 and 895 cm^{-1} (epoxide), δ 3·1—3·4 (2H, d, oxiran H), 2·4—1·55 (3H, m, 4-H_2 and 1-H), and 0·9—1·2 (5H, m, Me with 5- and 6-H).

The epoxide (1·1 g, 0·01 mol) in ether was added dropwise to lithium aluminium hydride (1 g, 0·026 mol) in ether (25 ml) at 0°. The mixture was heated under reflux overnight when work-up yielded *endo*-6-methylbicyclo[3.1.0]-hexan-3-ol, $\nu_{max.}$ 3400 cm^{-1} (OH). δ 4·3—4·0 (1H, t, 3-H), 2·2 (1H, s, OH), 1·7—2·0 (4H, m, 2 × CH_2), 1·6—1·2 (2H, m, 1- and 5-H), and 0·7—0·95 (4H, m, Me and 6-H). The alcohol gave a 3,5-dinitrobenzoate, m.p. 136—137° (from methylcyclohexane) (Found: C, 55·0; H, 4·65; N, 9·3. Calc. for $C_{14}H_{14}N_2O_6$: C, 54·9; H, 4·6; N, 9·1%).

4-*Benzyloxycyclohexanone*.—Cyclohexane-1,4-diol (58 g, 0·5 mol) was heated under reflux in toluene (160 g) with stirring whilst sodium (12·7 g, 0·55 mol) was cautiously added little by little. After a further 4 h heating benzyl chloride (70 g, 0·55 mol) was added and refluxing was continued for 3 h. After cooling and the careful addition of water (100 ml) the organic layer was separated and combined with a benzene extract (50 ml) of the aqueous layer. Distillation gave the required benzyloxy-alcohol (61 g, 51%), b.p. 130—140° at 0·1 mmHg. The alcohol (56 g, 0·26 mol) in acetone (250 ml) was oxidised with Jones reagent to give the cyclohexanone (49 g, 88%) b.p. 133—137° at 0·65 mmHg.

4-*Benzyloxy*-1-*deuteriocyclohexyl Toluene*-p-*sulphonate*.— 4-Benzyloxycyclohexanone (45 g, 0·22 mol) in ether (200 ml) was added dropwise to a stirred solution of lithium aluminium deuteride (2·5 g, 0·055 mol) in ether (100 ml) and the mixture was heated under reflux for 12 h. Work-up in the usual way gave crude 4-benzyloxy-1-deuteriocyclohexanol (44·5 g, 99%). The n.m.r. spectrum was similar to that for the normal benzyloxycyclohexanol except that no signal at δ 3·2—3·7 (CHOH) was present. The alcohol in dry pyridine (400 ml) was treated with toluene-*p*-sulphonyl chloride (47·5 g, 0·25 mol) overnight to yield the crystalline benzyloxy-tosylate (65 g, 90%), m.p. 71—72° (from benzene–ligroin) (Found: C, 66·3; H, 6·5; S, 9·4. $C_{20}H_{23}DO_4S$ requires C, 66·6; H, 6·7; S, 8·9%), δ 7·9—7·1 (9H, m, aromatic H), 4·5 (2H, s, $ArCH_2O$), 3·2—3·6 (1H, m, CHO), 2·45 (3H, s, Ar*Me*), and 1·4—2·1 (8H, m, cyclohexane ring H). (It appeared that the reduction had given largely one epimer.)

Hydrogenolysis of the Benzyloxycyclohexyl Tosylate.—The deuteriated tosylate (1 g, 0·03 mol) in ethyl acetate–absolute ethanol (1 : 1) (25 ml) was boiled with Raney nickel (0·3 g) for 10 min to remove catalyst poisons. The nickel was filtered off, and replaced by 5% palladium on charcoal (2 g) and the mixture was shaken in hydrogen at atmospheric pressure. As uptake of hydrogen began to slow the catalyst was renewed periodically until the uptake reached the theoretical 1 mol. equiv. of hydrogen. Work-up yielded the crude hydroxy-tosylate (0·7 g, 93%) as a low-melting solid, showing one spot by t.l.c., δ 7·1—7·9 [4H, $(AB)_2$, aromatics], 3·5—3·9 (1H, m, CHOH), 2·85 (OH), 2·4 (3H, s, Me), and 2·1—1·1 (8H, m, remainder).

5-*Deuteriobicyclo*[3.1.0]*hexan*-2-*one*.—Oxidation of the deuteriated tosyloxycyclohexanol (10 g, 0·037 mol) in acetone (100 ml) with Jones reagent gave 4-deuterio-4-tosyloxycyclohexanone from benzene, m.p. 91—95° (6·7 g, 67%). This ketone in tetrahydrofuran was treated with sodium hydride (50% in Nujol; 0·65 g, 0·026 mol) and two drops of ethanol were added. The mixture was stirred and heated under reflux in a nitrogen atmosphere for 5 h. Sodium toluene-*p*-sulphonate and unchanged sodium hydride were filtered off and the filtrates after removal of solvent gave the bicyclohexanone (1·1 g, 30%), b.p. 69° at 15 mmHg, M^+ 97, δ 0·7—1·3 (2H, m, cyclopropyl CH_2) and 1·5—2·3 (5H, m, remainder).

Deuterium Scrambling Experiment.—5-Deuteriobicyclohexan-2-one (2 g, 0·021 mol) was reduced with sodium borohydride to a mixture of *endo*- and *exo*-2-alcohols (1·7 g, 85%). Treatment of this mixture with phosphorus pentachloride gave the crude chlorides (0·7 g, 30%) with *exo*- and *endo*-chloride ratio of 1·8 : 1 contaminated with 4-chlorocyclohexene (5%). Solvolysis of these chlorides (0·7 g) in 70% aqueous acetone (50 ml) containing sodium hydrogen carbonate (0·8 g) for 24 h, followed by saturation with sodium chloride and extraction with pentane gave the crude bicyclohexanols and cyclohex-3-enol (0·61 g), in ratio of 67% *exo*-, 23% *endo*-ol, and 9·5% cyclohex-3-enol. The alcohols (0·6 g) in ether (25 ml) were stirred at 0° whilst Jones reagent (8N in O; 1·75 ml) was added dropwise and then for a further 0·5 h. Neutralisation with sodium hydrogen carbonate and extraction with ether gave the crude bicyclohexan-2-one which was purified by preparative g.l.c. Deuterium loss was measured by comparing the mass spectra of samples of starting ketone and the final product using the ratio of M to $M - 1$ peaks (Table 3).

TABLE 3

Mass spectrum of 5-deuteriobicyclo[3.1.0]hexan-2-one

$M/M - 1$

Sample	Before reaction sequence	After reaction sequence	Deuterium loss (%)
1	100/7·5	100/9·1	0·8
2	100/10·3	100/11·0	0·4

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