155. Synthesis and Rearrangement of 7-Halobicyclo[3.2.0]hept-2-en-6-ols

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(21.III.77)

Synthese und Umlagerung von 7-Halo-bicyclo[3.2.0]hept-2-en-6-olen

Zusammenfassung

Die Reaktion von verschiedenen 7-halogen-substituierten Bicyclo[3.2.0]hept-2-en-6-onen mit komplexen Metallhydriden oder mit Methylmagnesiumiodid zu den entsprechenden 7-Halo-bicyclo[3.2.0]hept-2-en-6-olen verläuft unter Angriff des Nucleophils *trans* zum Halogen, um dem vicinalen Kohlenstoff-Halogen-Dipol auszuweichen. In Gegenwart von starken Basen unterliegen die Halohydrine einer Umlagerung, die je nach der durch die intramolekularen Wechselwirkungen bedingten Konformation, entweder unter Hydridverschiebung zu Bicyclo[3.2.0]hept-2-en-6-onen oder, unter Ringverengung, zu Bicyclo[3.1.0]hex-2-en-6-carbaldehyden führt.

1. Introduction. – Base-catalysed rearrangements of simple 2-halocyclobutanones and -ols [1], of 7-halobicyclo[3.2.0]hept-2-en-6-ones [2] [3] and of 7,7-dichlorobicyclo[3.2.0]hept-2-en-6-ols [4] have been reported. In this paper we describe the synthesis and configurational assignment of various 7-halobicyclo[3.2.0]hept-2-en-6-ols and the rearrangements observed by treatment of these compounds with base (preliminary communication [5]).

2. Synthesis of 7-halobicyclo[3.2.0]hept-2-en-6-ols. – The required reactants, 7-*endo*-halobicyclo[3.2.0]heptenones **1, 3, 4** and 7-*exo*-halobicyclo[3.2.0]heptenones **10** to **12**, were prepared by cycloaddition of the appropriate haloketenes to cyclopentadiene and purified (as previously described) [3] [6] [7]. The preparation of 7-*endo*-chloro-7-*exo*-deuteriobicyclo[3.2.0]heptenone **2** is described in the experimental section.

Lithium aluminium hydride or sodium borohydride reduction of the 7-*endo*-haloketones **1** to **4** proceeded stereospecifically at room temperature to give the corresponding 7-*endo*-halobicyclo[3.2.0]hepten-6-*endo*-ols **5** to **8** respectively in

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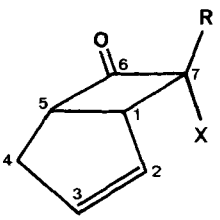
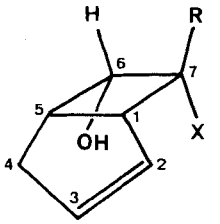
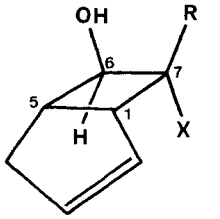


1 X = Cl, R = H
2 X = Cl, R = D
3 X = Cl, R = CH_3
4 X = Br, R = CH_3



5 X = Cl, R = H
6 X = Cl, R = D
7 X = Cl, R = CH_3
8 X = Br, R = CH_3



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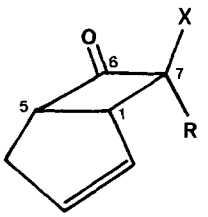
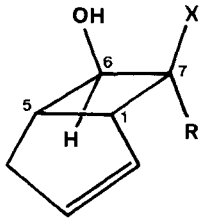
good yields[3]). No evidence was obtained for the formation of even small amounts of the epimeric *exo*-alcohols **9**.

Obviously, the well known steric factor leading to the preferential attack of hydride carriers from the *exo*-face of bicyclo[3.2.0]hepten-6-ones [4] [8] is reinforced by the presence of the electronegative 7-*endo*-halogen atom, the hydride carrier usually approaching the carbonyl group in *a*-haloketones in order to maintain a maximal distance from the carbon-halogen dipole [9].

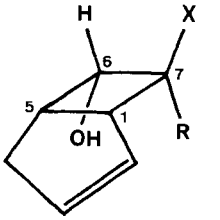
In the case of the *exo*-haloketones **10** to **12**, the two factors, steric and dipole effects, are opposed. Reduction of **10** and **11** with $LiAlH_4$ or $NaBH_4$ gave predominantly the 6-*exo*-alcohols **13** and **14** respectively, purified by bulb tube distilla-



10 X = Cl, R = CH_3
11 X = Br, R = CH_3
12 X = Cl, R = C_6H_5



13 X = Cl, R = CH_3
14 X = Br, R = CH_3
15 X = Cl, R = C_6H_5

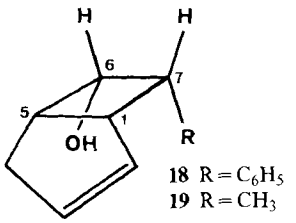


16 X = Cl, R = CH_3
17 X = Cl, R = C_6H_5

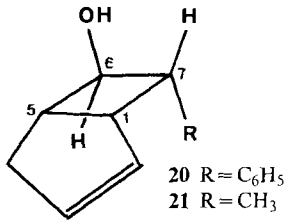
tion or fractional crystallization. Reduction of 7-*endo*-phenyl-7-*exo*-chloroketone **12** with $NaBH_4$ gave a crystalline chlorohydrin with the 6-*exo*-alcohol structure **15** on the basis of the coupling constants for H–C(6) ($J = 6.0$ with H–C(5) and $J = 1.5$ Hz with H–C(1)) and the chemical shift ($\delta = 3.00$) of H–C(5) (see section 3). Reduction of **12** with $LiAlH_4$ gave the chloro-*exo*-alcohol **15** (but no chloro-*endo*-alcohol **17**), and 7-*endo*-phenylbicyclo[3.2.0]hept-2-en-6-*endo*-ol **(18).** This alcohol **18** was the only $LiAlH_4$ reduction product (75%) of 7-*endo*-phenylbicyclo[3.2.0]hept-2-en-6-one **(22).**

These results indicate that the directive power of the carbon-halogen dipole overcomes the bulk effect due to both the cyclopentene ring and the 7-*endo*-substituent so promoting *endo*-attack by simple hydride carriers.

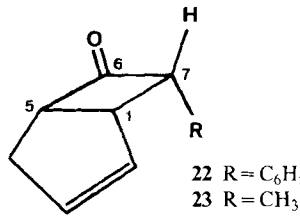
[3]) Details for the preparation of the halohydrins **5** and **7** have been given [7].



18 R = C_6H_5
19 R = CH_3



20 R = C_6H_5
21 R = CH_3



22 R = C_6H_5
23 R = CH_3

The bulkier lithium tri-*t*-butoxyaluminium hydride reduced the methylchloroketone **10** less stereoselectively, the *exo*- and *endo*-alcohols **13** and **16** being formed in a 3:2 ratio. In this way it was possible to obtain the chloroalcohol **16**, the only *trans*-halohydrin in this series; it was separated in 91% purity by low temperature fractional crystallization from the above mixture of **13** and **16**.

When the bicyclo[3.2.0]heptenones **1**, **3** and **12** were treated under more vigorous conditions (*e.g.* $LiAlH_4$ in boiling tetrahydrofuran) the initial reduction was followed by rearrangement and further reduction (section 7).

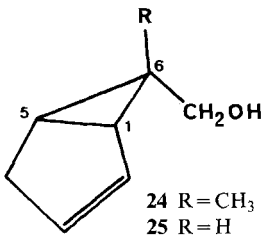
3. Configurational assignments of bicyclo[3.2.0]hept-2-en-6-ols. – The configuration of the hydroxyl group in halohydrins **5** to **8** and **13** to **16** was assigned by examination of the NMR. spectra [10]. Some criteria upon which the present configurational assignments were made [4] may be summarized as follows: a) The vicinal coupling constant between H–C(5) and H–C(6) is always greater for the 6-*endo*- than for the 6-*exo*-alcohols; but on this basis assignments are only valid if both 6-epimeric alcohols are available, *e.g.* **13** and **16**, **19** and **21**; b) The transannular coupling constant between H–C(1) and H–C(6) is greater for the 6-*endo*- (~2.5 Hz) than for the 6-*exo*-alcohols (~1 Hz); c) After consideration of inductive and anisotropic effects due to *cis*- or *trans*-substituents at C(7), the chemical shift of H–C(6) in an *endo*-position is at higher field than that of *exo*-H–C(6), possibly due to the anisotropic effect of the adjacent five-membered ring; d) The H–C(5) signal is at higher field in the 6-*exo*-alcohols (*e.g.* **13**, **20** and **21**, $\delta = 3.0$–2.5) than in the 6-*endo*-isomers (*e.g.* **16**, **18** and **19**, $\delta = 3.6$–3.2): $\Delta\delta$ (H–C(5))$_{endo\text{-}exo} \approx 0.6$.

Further evidence for the configuration of the hydroxyl group of the halohydrins **8** and **13** to **15** was obtained by dehalogenation using tri-*n*-butyltin hydride in boiling benzene, conditions not expected to affect the configuration at C(6): Both *exo*-haloalcohols **13** and **14** were converted to 7-*endo*-methylbicyclo[3.2.0]hept-2-en-6-*exo*-ol (**21**), identical by NMR. [11] to the compound prepared by *Berson et al.* [12].

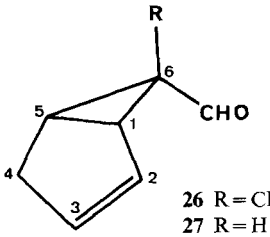
Tri-*n*-butyltin hydride reduction of the *endo*-bromoalcohol **8** gave a mixture of the dehalogenated product, 7-*endo*-methylbicyclo[3.2.0]hept-2-en-6-*endo*-ol (**19**), and a rearranged product, 6-*exo*-methylbicyclo[3.1.0]hex-2-en-6-*endo*-carbinol (**24**), separated by column chromatography. The pure *endo*-alcohol **19** was identical to a sample obtained by an unambiguous method [6]. The *exo* to *endo* inversion of the methyl group at C(7) in the reaction **8** → **19** is rationalized by postulating an intermediate radical [13] which, under kinetic control, preferentially abstracts a hydrogen atom from the *exo* face[4]). The rearranged alcohol **24** was identical to

[4]) Treatment of the haloketones **3** and **4** with tri-*n*-butyltin hydride in benzene furnishes 7-*endo*-methylbicyclo[3.2.0]hept-2-en-6-one (**23**) almost exclusively [14].

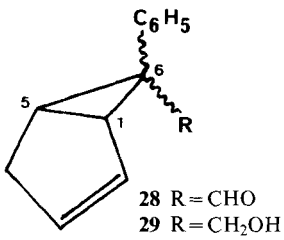
the product obtained on reduction of the *endo*-aldehyde **26** (see section 4) with $LiAlH_4$. By treatment of the corresponding *endo*-chloroalcohol **7** with tri-*n*-butyltin



24 R = CH_3
25 R = H



26 R = CH_3
27 R = H or D

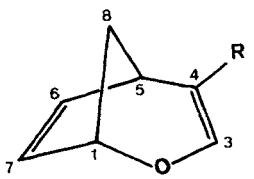


28 R = CHO
29 R = CH_2OH

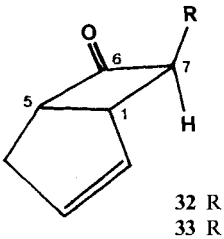
hydride, only the rearranged compound **24** was obtained (68%). The tri-*n*-butyltin hydride-induced rearrangements of **7** or **8** to **24** are stereospecific; there was no evidence for the formation of the 6-*exo* epimer.

Similar treatment of 7-*endo*-phenyl-7-*exo*-chlorobicyclo[3.2.0]hept-2-en-6-*exo*-ol (**15**) gave a mixture of two alcohols, inseparable by chromatography on silica gel. However, the NMR. spectrum of the mixture indicated the presence (30%) of the ring contracted alcohol **29**[5]), obtained in a pure state by vigorous $LiAlH_4$ treatment of the *endo*-phenyl-*exo*-chloroketone **12** (see section 7). The major component (70%) was the unrearranged, dechlorinated 6-*exo*-alcohol **20**, the structure of which was assigned mainly on the basis of the chemical shift ($\delta = 2.69$) of the H–C(5) multiplet, at higher field than that ($\delta = 3.24$) of the 6-*endo*-alcohol **18** (*cf.* section 2).

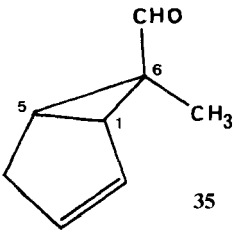
4. Base-catalysed rearrangement of the chlorohydrins. – The eight halohydrins (**5** to **8** and **13** to **16**) were all susceptible to base-catalysed rearrangement[6]). A summary of reaction conditions, products and yields is presented in *Table 1*.



30 R = H or D
31 R = CH_3



32 R = CH_3
33 R = C_6H_5



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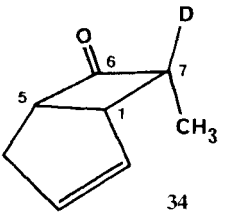

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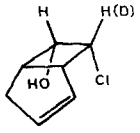
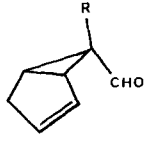
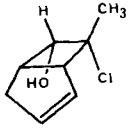
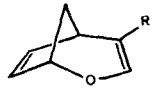
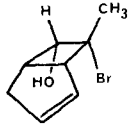
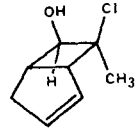
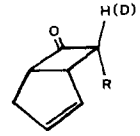
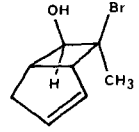
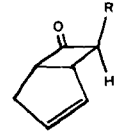
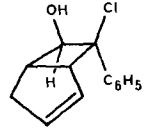
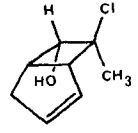
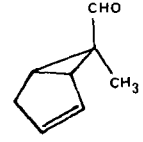
[5]) The configuration at C(6) of **29** was not established (see, however, footnote 8 in section 7).

[6]) Experimental details concerning the base-catalysed rearrangement of chlorohydrins **5** and **7** have been presented [7].

Table 1. *Rearrangement of 7-halobicyclo[3.2.0]hept-2-en-6-ols with base*

Compound	Reaction conditions	Products	Yield %
5 	a)	 **30** ⇄ **27**	81
	e)	**30** ⇄ **27**	60
6	f)	**30** ⇄ **27**	87
7 	a)	 **31** ⇄ **26**	80
	d)	**31** ⇄ **26**	53
	f)	**31** ⇄ **26**	91
			
8 	a)	R = H, D, CH_3 **31** ⇄ **26**	66

Compound	Reaction conditions	Products	Yield %
13 	a)	 **23** ⇄ **32** (70:30)	72
	b)	**23** ⇄ **32** (55:45)	85
	c)	**34** and **32**	
	d)	**23** ⇄ **32** (75:25)	66
	f)	**23** ⇄ **32** (66:34)	87
14 	a)	 **23** ⇄ **32** (70:30)	83
15 	a)	R = CH_3, C_6H_5 **22** ⇄ **33** (60:40)	50
16 	f)	 **35**	96

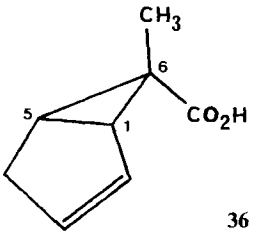
[a]) Stirring in 1N aqueous NaOH 2 h at RT., then extraction. [b]) Heating in 1N aqueous NaOH, steam distillation as formed. [c]) Stirring in 1N NaOD in D_2O 0.5 h at RT. [d]) Stirring with 1 mol of sodium methylsulfinyl carbanion in dimethylsulfoxide at 0°C. [e]) Stirring with sodium hydride in ether. [f]) Shaking 2 min with 8N aqueous KOH in methanol.

Three classes of halohydrins were available: a) the *endo*-hydroxy-*endo*-halobicyclo[3.2.0]hept-2-enes (*endo, endo*-halohydrins **5** to **8**); b) the *exo*-hydroxy-*exo*-halobicyclo[3.2.0]hept-2-enes (*exo, exo*-halohydrins **13** to **15**); c) the *endo*-hydroxy-*exo*-halobicyclo[3.2.0]hept-2-ene (*exo, endo*-halohydrin **16**).

No example of an *exo*-hydroxy-*endo*-halobicyclo[3.2.0]hept-2-ene (**9**) was available.

Compounds of each class gave different results with base: a) the four *endo, endo*-halohydrins rearranged *via* ring contraction to give the 6-*endo*-isomers of bicyclo[3.1.0]hex-2-en-6-carbaldehydes, in valence tautomeric equilibrium with the corresponding 2-oxabicyclo[3.2.1]octa-3,6-dienes; b) the three *exo, exo*-halohydrins rearranged *via* intramolecular hydride shift to give 7-epimeric mixture of 7-monosubstituted bicyclo[3.2.0]hept-2-en-6-ones; c) the *exo, endo*-halohydrin rearranged *via* ring contraction to give the 6-*exo*-isomer of a bicyclo[3.1.0]hex-2-en-6-carbaldehyde.

5. Characterization of the base-catalysed rearrangement products. – The valence tautomeric mixture **30** ⇄ **27** was identical to the mixture prepared by *Meinwald et al.* [7] [15]. In the methyl-substituted series, the NMR. spectrum of the valence tautomeric mixture **31** ⇄ **26** exhibited a similar spin-system to that observed for the mixture **30** ⇄ **27.** Furthermore, silver oxide converted **31** ⇄ **26** into 6-*exo*-methylbicyclo[3.1.0]hex-2-en-6-*endo*-carboxylic acid (**36**) [3] [7]. The structure of the 6-*exo*-aldehyde **35** was ascertained from spectral data, which showed the absence of a valence tautomeric enol ether, and by silver oxide oxidation to 6-*endo*-methylbicyclo[3.1.0]hex-2-en-6-*exo*-carboxylic acid (**37**), identical with authentic material [3] [7].



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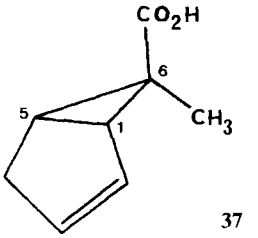

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The epimeric 7-methylbicycloheptenones **23** and **32** were separated by preparative gas chromatography: the major component, the *endo*-epimer **23,** was identical to the product obtained on cycloaddition of methylketene and cyclopentadiene [6] [16] and the minor component had spectral characteristics in accord with the *exo*-methyl structure **32.**

The presence of deuterium at C(7) in ketone **34** (see *Table 1*) was established by comparison of its NMR. signal due to CH_3–C(7) (broadened singlet at $\delta = 0.99$) with the corresponding signal in the non-deuterated ketone **23** (doublet at $\delta = 0.99$, $J = 7.5$ Hz). The ratio of epimeric 7-methylbicycloheptenones **23** (or **34**) to **32** was estimated by gas chromatography.

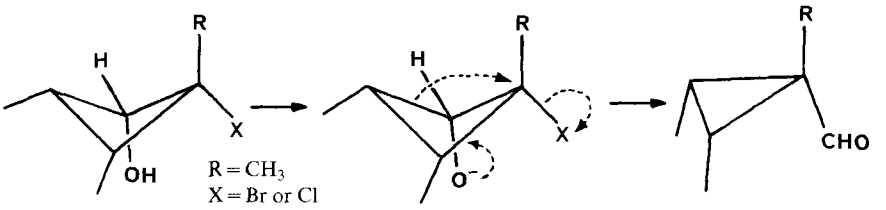
The epimeric 7-phenylbicycloheptenones **22** and **33** were identical (NMR.) with the mixture obtained from the cycloaddition of phenylketene and cyclopentadiene [6]. The ratio of epimers **22:33** obtained from **15** was estimated by integration

of the signals due to the *exo*-H–C(7) ($\delta = 4.30$) of the *endo*-phenylketone **22** and the *endo*-H–C(7) ($\delta = 3.86$) of the *exo*-phenylketone **33** in the NMR. spectrum of the product mixture in benzene.

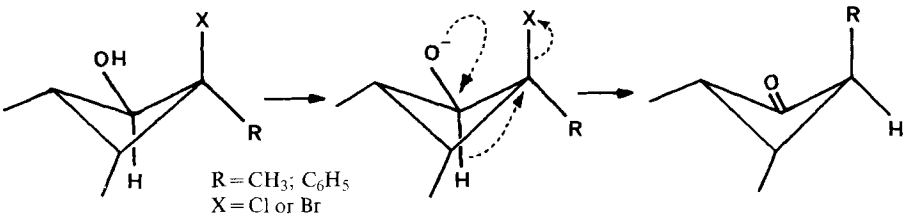
6. Mechanisms of rearrangement. – Stereoelectronic reasons lead to the following alternatives for the base-catalysed reaction of cyclobutane-halohydrins with a secondary alcohol function (see *Schemes 1* to *6*): for the *cis*-isomers, 1,2-hydride shift to cyclobutanones, for the *trans*-isomers, epoxide formation, and for both *cis*- and *trans*-isomers, ring contraction to cyclopropane-carbaldehydes. From the bicycloheptene-halohydrins discussed in this paper, ring contraction of the *exo*-halo compounds would be expected to lead to *exo*-carbaldehydes, that of the *endo*-halo compounds to *endo*-carbaldehydes.

With the three diastereomeric classes of bicycloheptene-halohydrins we observe that a) *endo,endo*-halohydrins *(cis)* prefer ring contraction (to *endo*-aldehydes, *Scheme 1*) over hydride shift *(Scheme 4)*; b) *exo,exo*-isomers *(cis)* prefer hydride shift *(Scheme 2)* over ring contraction *(Scheme 5)*, and c) the *exo,endo*-halohydrin prefers ring contraction (to *exo*-aldehyde, *Scheme 3*) over epoxide formation *(Scheme 6)*. The transition state conformations suggested in *Schemes 1* to *6* parallel corresponding situations found in 5- and 6-membered ring systems [17].

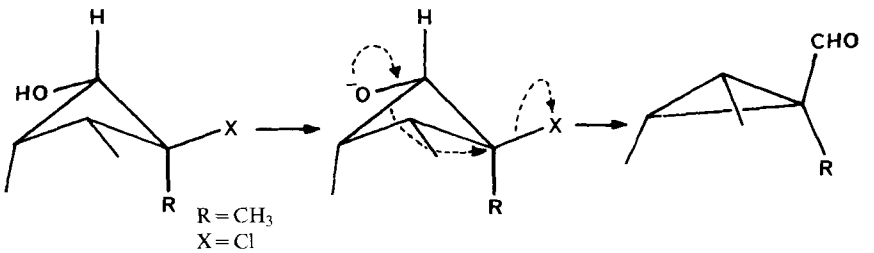
Scheme 1



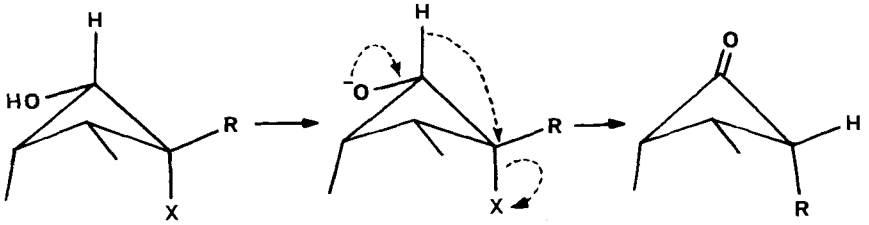
Scheme 2



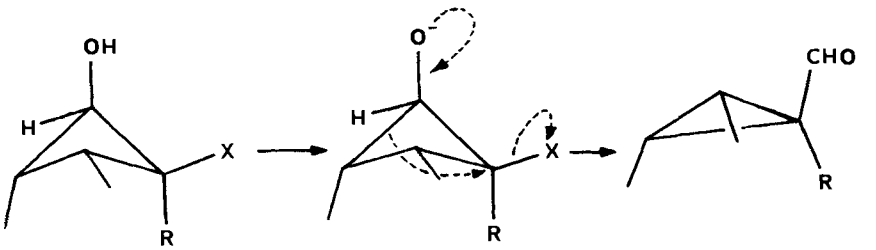
Scheme 3



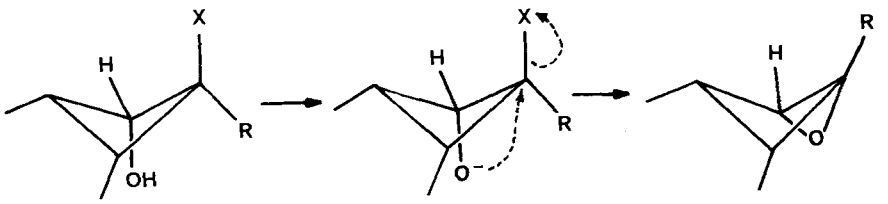
Scheme 4



Scheme 5



Scheme 6



Two possible rationalizations are in agreement with our results. 1) If ring contraction of such systems is generally favoured over the alternative paths[7]), the exception, hydride shift with the *exo,exo*-halohydrins *(Scheme 2)*, could be due to bulk interference of the 7-*endo*-substituent and the 5-membered ring atoms in the ring contraction path *(Scheme 5)*. 2) If ring contraction is favoured in the *trans*-halohydrins and hydride shift in the *cis*-isomers, the ring contraction with the *endo, endo*-halohydrins *(Scheme 1)* is an exception, which could be explained by bulk interference of solvation of the chloride ion leaving from the *endo*-side in the hydride shift path *(Scheme 4)*.

The intramolecular nature of the hydride shift in the rearrangement of chlorohydrin **13** to ketone **32** was demonstrated by performing the reaction in D_2O containing NaOD. The presence of deuterated *endo*-methylketone **34** and undeuterated *exo*-methylketone **32** in the product illustrates that a 1,2-suprafacial shift *(Scheme 2)* to the primary *exo*-methylketone [3] [14] is followed by base-catalysed isomerization to the *endo*-methylketone.

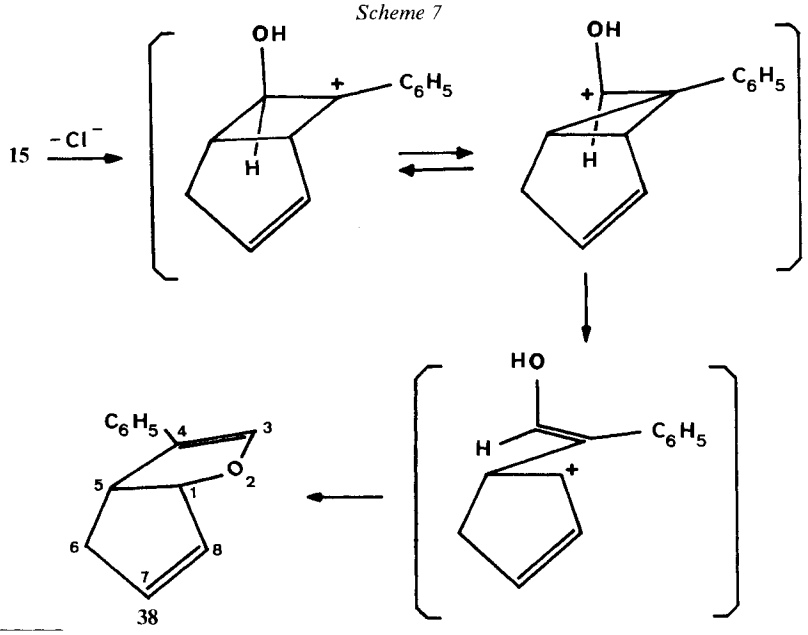
[7]) The 6-epimeric 7,7-dichloro-6-hydroxybicyclo[3.2.0]heptane derivatives prefer ring contraction over other paths [4]. Of the two alternative modes of ring contraction, elimination of the chlorine atom *trans* to the hydroxyl group is favoured.

7. One-step conversion of 7-halobicyclo[3.2.0]hept-2-en-6-ones into bicyclo[3.1.0]hex-2-ene-6-carbinols. – 7-Halobicyclo[3.2.0]hept-2-en-6-ones were converted into bicyclo[3.1.0]hex-2-ene-6-carbinols with $LiAlH_4$ in boiling tetrahydrofuran, ketones **1** and **3** giving the alcohols **25** and **24** respectively in ~65% yield. Similar treatment of the phenylchloroketone **12** yielded a separable mixture of 20% of the dechlorinated cyclobutanol **18** and 44% of the ring contracted alcohol **29**[8]); the constitution of the latter compound was ascertained from spectral data. We believe that these reactions first involve reduction of the carbonyl group in **1**, **3** and **12** to a hydroxyl group (**5**, **7** and **15**) with subsequent ring contraction under the reaction conditions to the carbaldehydes **27**, **26** and **28**, which are then further reduced to the observed alcohols **25**, **24** and **29**[9]).

8. Acid-catalysed rearrangement of 7-*endo*-phenyl-7-*exo*-chlorobicyclo[3.2.0]hept-2-en-6-*exo*-ol (15). – The unsubstituted and alkylchlorohydrins **5**, **7**, **8**, **13** and **14** are stable to dilute acid and aqueous silver nitrate at RT. In contrast, 7-*endo*-phenyl-7-*exo*-chlorobicyclo[3.2.0]hept-2-en-6-*exo*-ol (**15**) readily rearranges, with loss of HCl, to the cyclic enol ether **38** when treated with 4N HCl, or aqueous silver nitrate, or when the alcohol **15** is chromatographed on silica gel in benzene.

A possible course of this rearrangement is shown in *Scheme 7*. Acid-catalysed conversion of bicyclo[3.1.0]hex-2-ene-carbaldehydes into 2-oxabicyclo[3.3.0]octa-3,7-dienes, which correspond to the last two steps of *Scheme 7*, are known [18].

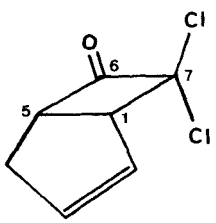
Scheme 7



[8]) From the configuration of **12** it would be expected that **29** carries the 6-phenyl group in *endo* position.

[9]) This pathway from **12** to **29** is in contrast with the observed hydride shift under aqueous base conditions of the product **15** from the mild $LiAlH_4$ reduction of **12**. There is no reason to assume that the more drastic hydride reduction conditions produced the *endo*-alcohol **17**.

9. Reaction of 7-halobicyclo[3.2.0]heptenones with methylmagnesium iodide and rearrangements of the methylhalohydrin products. – The reaction of 7,7-dichlorobicyclo[3.2.0]hept-2-en-6-one **39** with methylmagnesium iodide to give a mixture of the two methylchlorohydrins **40** and **42** in a ratio of 67:33 and the rearrangements of the separated isomers have been discussed [4].



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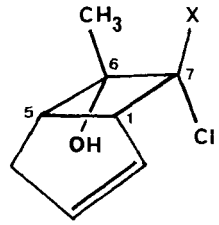
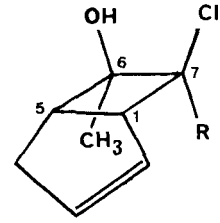
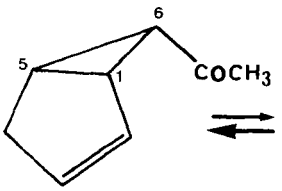


40 X = Cl
41 X = H



42 R = Cl
43 R = CH_3

The same *Grignard* reaction with the ketone **1** gave the halohydrin **41** as the sole product. Treatment with base converted **41** to the valence tautomeric mixture of the *endo*-acetyl derivative **44** and the enol ether **45** (92:8, NMR. in $CDCl_3$). Reaction of 7-*endo*-methyl-7-*exo*-chlorobicyclo[3.2.0]hept-2-en-6-one (**10**) with methylmagne-



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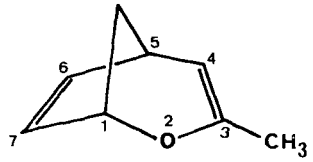

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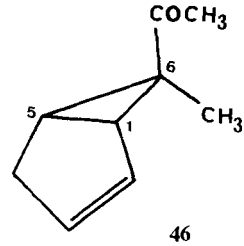

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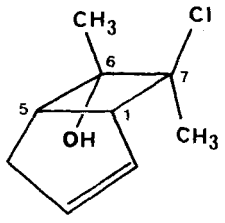
sium iodide at RT. yielded a ketone, while at lower temperatures starting material was recovered. From spectral data the ketone was assigned the rearranged structure **46**. Both the *exo*-alcohol **43** *(cf. Scheme 5)* and the *endo*-alcohol **47** *(cf. Scheme 3)* could be intermediates in the formation of 6-*endo*-methyl-6-*exo*-acetylbicyclo[3.1.0]hex-2-ene (**46**). Methylmagnesium iodide, however, probably does not experience severe steric restriction in approaching the *endo*-face of the carbonyl group [4] and, since *Grignard* reagents are influenced by vicinal dipoles in the same



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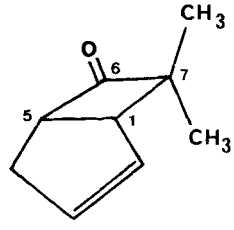

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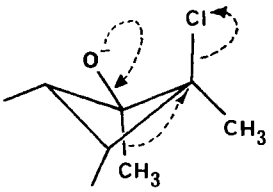
way (see above) as hydride reducing agents [20], it seems likely that the intermediate alcohol is the *cis*-halohydrin **43** with an *exo*-hydroxyl group.

Careful chromatography of the methyl *Grignard* product from **10** failed to reveal any dimethylketone **48**, which would have resulted from the shift of the methyl group analogous to the hydride shifts described above. The reluctance of the chlorohydrin **43** to undergo a methyl shift is probably due to the unfavourable interactions in a transition state which has the methyl group and the chlorine atom in



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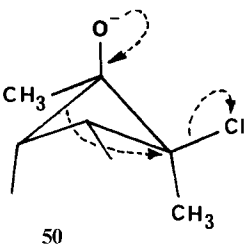

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trans-diaxial positions. The interference of the methyl group at C(6) with the 5-membered ring atoms in conformation **49** is presumably greater than a similar interaction involving the methyl group at C(7) in transition state **50**, which leads to ring contraction.

This work was supported by the *Science Research Council, Schweizerischer Nationalfonds zur Förderung der wissenschaftlichen Forschung* and by *Sandoz AG*, Basel.

Experimental Part

General. – *The purity* of all compounds was checked by gas liquid chromatography (GC.), thin layer chromatography (TLC.) and/or by their NMR. spectra. *Melting points* were determined in a *Büchi* apparatus (system *Dr. Tottoli*) and are uncorrected. All compounds not described as impure gave correct elemental analyses for carbon and hydrogen, and, when determined, for chlorine or bromine (Mr. *H. Frohofer* and his staff in Zürich and Mr. *J. Stewart* and his staff in Leeds).

NMR. spectra: NMR. spectra were recorded on a *Varian* A-60 or HA-100 spectrometer by Dr. *T. Winkler* and Mr. *P. Ziegler* of the NMR. laboratory Zurich University and on an A-60 in Leeds by Mrs. *C. Ingle*. They are reported on the δ-scale in ppm units (multiplicity, coupling constants in Hertz, number of protons H, (assignment); tetramethylsilane was used as internal standard ($\delta = 0$). Peak shapes are denoted by the following symbols: s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet.

GC.: GC.-A: analytical, 1520-B *(Aerograph)*, flame ionisation detector, oven temp. 63°, column 3 ft. × 1/8 in., 5% silicone QF-1 on chromosorb W-AW/DMCS 100/120 mesh, 25 ml/min N_2. – *GC.-B:* analytical, 1520-B *(Aerograph)*, flame ionisation detector, oven temp. 100°, column 5 ft. × 1/8 in., 5% emulphor O on chromosorb W-AW/DMCS 100/120 mesh, 25 ml/min N_2. – *GC.-C:* preparative, 1520-B *(Aerograph)*, thermal conductivity detector, oven temp. 180°, column 20 ft. × 3/8 in., 20% emulphor O on chromosorb W 60/80 mesh, 200 ml/min He. – *GC.-D:* the same as GC.-B but oven temp. 120°.

1. Preparation of 7-*exo*-deuterio-7-*endo*-chlorobicyclo[3.2.0]hept-2-en-6-one (2). – To a solution of 70.8 g (0.4 mol) 7,7-dichlorobicyclo[3.2.0]hept-2-en-6-one (**39**) in 250 ml CH_3COOD was added with stirring and cooling 26.2 g (0.4 mol) of Zn powder in small portions over a period of 30 min. The cold mixture was diluted with 1 l water and extracted with ether. The ethereal extract, after washing 4 times with water and once with saturated $NaHCO_3$ solution, was dried over Na_2SO_4 and concentrated. The residue was distilled at 12 Torr through a 10 cm *Vigreux* column to obtain 46.9 g (82%) 7-exo-*deuterio*-7-endo-*chlorobicyclo[3.2.0]hept-2-en-6-one* (**2**) as a colourless oil, b.p. 97–99°/12 Torr. – IR. (CCl_4):

1800*s*, C=O; 3060*w*; 2950*m*; 2910*m*; 2845*m*; 2195*w*, C–D. – The NMR. spectrum was identical with that of the 7-*exo*-protio-7-*endo*-chloro-derivative **1** [6] with the exception that the signal at 5.09 ppm (H–C(7)) was missing and the signal at 3.95–3.67 ppm (H–C(1) and H–C(5)) was simpler.

2. Preparation of substituted bicyclo[3.2.0]hept-2-en-6-ols. – *Method A.* To a stirred ice-cooled suspension of complex metal hydride in dry ether was added a solution of a 7-substituted bicyclo[3.2.0]hept-2-en-6-one in ether. The resulting suspension was stirred at RT. for 90 min. Water was added carefully, then 10% hydrochloric acid. The ether layer was separated and the aqueous phase extracted 3 times with ether. The combined ether fractions were dried (Na_2SO_4) and evaporated. The residue was distilled under reduced pressure to give the corresponding bicyclo[3.2.0]hept-2-en-6-ol.

Method B. The 7-substituted bicyclo[3.2.0]hept-2-en-6-one was added dropwise with stirring over 5 min to an excess of $NaBH_4$ in aqueous methanol (70%) at 0°. Reduction was usually complete within 5 min. (TLC.): the mixture was poured into water and then extracted with dichloromethane and worked up as usual. The bicyclo[3.2.0]hept-2-en-6-ols were purified by bulb tube distillation or fractional crystallization.

2.1. 7-endo-*Chlorobicyclo[3.2.0]hept-2-en-6*-endo-*ol* (**5**). – *Method A.* With $LiAlH_4$ [7]. *Method B.* The chloroketone **1** (5 g) with $NaBH_4$ (0.75 g) gave the *endo*-alcohol **5** (4.9 g, 96%), m.p. 16.5–17°, b.p. 90° (air-bath)/15 Torr, identical with the product obtained by method A; *p*-bromobenzoate of **5**, m.p. 79–80°.

2.2. 7-exo-*Deuterio*-7-endo-*chlorobicyclo[3.2.0]hept-2-en-6*-endo-*ol* (**6**). – *Method A.* From 28.7 g (0.2 mol) 7-*exo*-deuterio-7-*endo*-chlorobicyclo[3.2.0]hept-2-en-6-one (**2**) with 3.8 g (0.1 mol) $LiAlH_4$ in 200 ml ether, after distillation through a 10 cm *Vigreux* column: **6**, 25.2 g (86%) was obtained as a colourless oil, b.p. 56°/0.5 Torr. – IR. (CCl_4): 3550*m* OH; 3050*w*; 2960*m*; 2920*m*; 2835*w*; 2215*w*, C–D. – The NMR. spectrum was identical with that of protium analog **5** except that the signal at 4.74 (H–C(7)) was missing and the signals at 4.34 (H–C(6)) and at 3.65 (H–C(1)) were simplified.

2.3. 7-endo-*Chloro*-7-exo-*methylbicyclo[3.2.0]hept-2-en-6*-endo-*ol* (**7**). – *Method A.* With $LiAlH_4$ [7]. *Method B.* The 7-*endo*-chloro-7-methylketone **3** (1.0 g) with $NaBH_4$ (0.18 g) also gave the 6-*endo*-alcohol **7** (0.95 g) identical with the product obtained by method A; *p*-bromobenzoate of **7**, m.p. 91–92°.

2.4. 7-endo-*Bromo*-7-exo-*methylbicyclo[3.2.0]hept-2-en-6*-endo-*ol* (**8**). – *Method A:* 2.6 g (13 mmol) 7-*endo*-bromo-7-*exo*-methylbicyclo[3.2.0]hept-2-en-6-one (**4**) [6] [23] [24] and 0.9 g (22.6 mmol) $LiAlH_4$ in 80 ml ether yielded, after bulb tube distillation at 100–110°/0.8 Torr, 2.2 g (86%) **8**. – NMR. (100 MHz in CCl_4): 5.90 and 5.60 (2*m*, 2H, H–C(2), H–C(3)); 3.78 ($d \times d$, $J = 6.4$ and 3.5, 1H, H–C(6)); 3.5–2.8 (*m*, 2H, H–C(1), H–C(5)); 2.75 (*m*, 1H, *endo*-H–C(4)); 2.23 (*m*, 1H, *exo*-H–C(4)); 2.01 (*s*, 3H, CH_3–C(7)); 1.91 (*s*, 1H, OH).

2.5. 7-exo-*Chloro*-7-endo-*methylbicyclo[3.2.0]hept-2-en-6*-exo-*ol* (**13**). – *Method A:* 25.3 g (162 mmol) 7-*exo*-chloro-7-*endo*-methylbicyclo[3.2.0]hept-2-en-6-one (**10**) [6] [22] [23] and 3.06 g (80 mmol) $LiAlH_4$ in 300 ml ether yielded 17.8 g (70%) **13**, m.p. 44–45° (pentane, –20°). *Method B:* 7-*exo*-Chloro-7-methylketone **10** (7.5 g) with $NaBH_4$ (1.3 g) gave a mixture of 6-*exo*- (**13**) and 6-*endo*- (**16**) alcohols, 78:22 (NMR.). Crystallization from pentane at –50° gave the 6-*exo*-alcohol **13** as cubes, m.p. 43–44.5° (97% pure). The mother liquor of this crystallization was retained (see 2.9). – IR. (CCl_4): 3560, OH. – NMR. (100 MHz in CCl_4): 5.79 (*m*, 2H, H–C(2), H–C(3)); 3.58 ($d \times d$, $J = 6.0$ and 1.8, 1H, H–C(6)); 3.36 (*m*, 1H, H–C(1)); 2.83 (*m*, 1H, H–C(5)); 2.45 (*m*, 2H, H_2–C(4)); 1.54 (*s*, 3H, CH_3–C(7)). *p*-Bromobenzoate of **13**, m.p. 75–75.5°.

2.6. 7-exo-*Bromo*-7-endo-*methylbicyclo[3.2.0]hept-2-en-6*-exo-*ol* (**14**). – *Method A:* 2.0 g (9.9 mmol) 7-*exo*-bromo-7-*endo*-methylbicyclo[3.2.0]hept-2-en-6-one (**11**) [6] [23] [24] and 0.6 g (15.1 mmol) $LiAlH_4$ in 40 ml ether gave a colourless oil, b.p. 100–105°/0.07 Torr, 1.5 g (74%) **14**. – NMR. (100 MHz in CCl_4): 5.82 (*m*, 2H, H–C(2), H–C(3)); 3.48 (*m*, 2H, H–C(1), OH); 3.31 ($d \times d$, $J = 6.2$ and 2.0, 1H, H–C(6)); 2.87 (*m*, 1H, H–C(5)); 2.7–2.2 (*m*, 2H, H_2–C(4)); 1.74 (*s*, 3H, CH_3–C(7)).

2.7. 7-exo-*Chloro*-7-endo-*phenylbicyclo[3.2.0]hept-2-en-6*-exo-*ol* (**15**). – 2.7.1. *Method A.* From 2.0 g (9.2 mmol) 7-*exo*-chloro-7-*endo*-phenylbicyclo[3.2.0]hept-2-en-6-one (**12**) [6] [25] and 0.5 g (13 mmol) $LiAlH_4$ in 40 ml ether, 1.5 g of crude product was obtained, containing (NMR.) the chloro-*exo*-alcohol **15** and the dechlorinated *endo*-alcohol **18** (*ca.* 7:3) with some other impurities. Purer samples of **15** were obtained according to procedures 2.7.2 and 2.7.3. For **18**, see 2.8.

2.7.2 *Method B.* A solution of 6.56 g (30 mmol) 7-*exo*-chloro-7-*endo*-phenylbicyclo[3.2.0]hept-2-en-6-one (**12**) [6] [25] was stirred with 0.35 g (16 mmol) $LiBH_4$ in 50 ml ether at 0° for 20 min and then treated with water only, followed by a work-up as described in the general procedure to give 7.23 g of undistilled dried **15**. Distillation caused loss of HCl. The crude sample ("crude **15**") contained at least 70% of the chloro-*exo*-alcohol **15** and max. 10% (if any) of the 6-epimeric chloro-*endo*-alcohol **17**

(NMR.). – NMR. (60 MHz in $CDCl_3$): 7.25 (*m*, 5H, ArH); 5.9–5.3 (*m*, 2H, H–C(2), H–C(3)); 4.30 (*d*×*d*, *J* = 6.0 and 1.5, 1H, H–C(6)); 3.78 (*m*, 1H, H–C(1)); 3.00 (*m*, 1H, H–C(5)); 2.7–2.3 (*m*, 2H, H_2–C(4)).

2.7.3. *Method C.* The phenylchloroketone **12** (1.0 g) in methanol (150 ml) was added to $NaBH_4$ (0.5 g) and Na_2CO_3 (0.5 g) in water at 0°. Reduction was complete only after 1.5 h. The crude, unstable chloro-*exo*-alcohol **15** crystallized from pentane at −50° with considerable loss, m.p. 59–61°; *p*-bromobenzoate, of **15**, m.p. 106–107°.

2.8. 7-endo-*Phenylbicyclo[3.2.0]hept-2-en-6*-endo-*ol* **(18).** – *Method A:* 2.66 g (15.6 mmol) 7-*endo*-phenylbicyclo[3.2.0]hept-2-en-6-one **(22)** [6] [14] and 1.5 g (39.5 mmol) $LiAlH_4$ in 50 ml ether gave, after distillation (bulb tube) at 155°/0.1 Torr, 2.0 g (75%) **18** as a viscous oil. – NMR. (100 MHz in CCl_4): 7.25 (*m*, 5H, ArH); 5.95 (*m*, 2H, H–C(2), H–C(3)); 4.70 (*d*×*d*×*d*, *J* = 3.0 and 6.7 and 7.3, 1H, H–C(6)); 4.11 (*d*×*d*, *J* = 7.5 and 7.3, 1H, H–C(7)); 3.75 (*m*, 1H, H–C(1)); 3.24 (*m*, 1H, H–C(5)); 2.8–2.2 (*m*, 2H, H_2–C(4)).

2.9. 7-exo-*Chloro*-7-endo-*methylbicyclo[3.2.0]hept-2-en-6*-endo-*ol* **(16).** – *Method A.* From 5.5 g (35 mmol) 7-*exo*-chloro-7-*endo*-methylbicyclo[3.2.0]hept-2-en-6-one **(10)** [6] [22] [23] and 18.0 g (70.6 mmol) lithium tri-*t*-butoxyaluminium hydride in 150 ml ether, after distillation (bulb tube) at 100°/11 Torr, 4.3 g (78%) of a mixture containing **13** and **16** (3:2, NMR.) was obtained. The *exo*-alcohol **13** was identified by comparison (NMR.) with a pure sample of **13** (2.5). The remaining signals in the mixture were assigned to the *endo*-alcohol **16** (see below). *Method B.* The pentane mother liquors from the crystallization of the 6-*exo*-alcohol **13**, after the $NaBH_4$ reduction of **10** (2.5) were kept at −50° for 7 weeks, when the 6-*endo*-alcohol **16** crystallized in long needles. After decantation and washing with cold pentane the *endo*-alcohol **16** was 91% pure (NMR.). It was an unstable oil at RT. and was stored at −20°. – NMR. (60 MHz in $CDCl_3$): 5.93 and 5.72 (2*m*, 2H, H–C(2), H–C(3)); 4.53 (*m*, 1H, H–C(6)); 3.4 (*m*, 2H, H–C(5), H–C(1)); 2.48 (*m*, 2H, H_2–C(4)); 2.98 (*s*, 1H, OH); 1.38 (*s*, 3H, CH_3–C(7)). *p*-Bromobenzoate of **16**, m.p. 89–90°.

3. **Tri-*n*-butyltin hydride treatment of 7-halobicyclo[3.2.0]hept-2-en-6-ols.** – A solution of 1 mol equivalent 7-halobicyclo[3.2.0]hept-2-en-6-ol and 1.05 mol equivalent tri-*n*-butyltin hydride in 50 ml benzene was refluxed for 48 h. The solvent was evaporated and the residue distilled at reduced pressure in a bulb tube, leaving as a residue the higher boiling tri-*n*-butyltin hydride and tri-*n*-butyltin chloride.

3.1. *Treatment of* 7-endo-*chloro*-7-exo-*methylbicyclo[3.2.0]hept-2-en-6*-endo-*ol* **(7)** (1.3 g, 8.2 mmol) with 2.5 g (8.6 mmol) tri-*n*-butyltin hydride gave 0.7 g (68%) 6-*exo*-methylbicyclo[3.1.0]hex-2-en-6-*endo*-carbinol **(24)** as a colourless oil, b.p. 80–90°/11 Torr, which solidified at low temperatures. The IR. and NMR. spectra were identical to those described under 5.2.

3.2. *Treatment of* 7-endo-*bromo*-7-exo-*methylbicyclo[3.2.0]hept-2-en-6*-endo-*ol* **(8)** (1.3 g, 6.4 mmol) with 2.0 g (6.7 mmol) tri-*n*-butyltin hydride gave a mixture that was chromatographed on silica gel in ethyl acetate/benzene 1:9 to yield 0.2 g (25%) 7-*endo*-methylbicyclo[3.2.0]hept-2-en-6-*endo*-ol **(19)**, b.p. 90–100°/11 Torr, and 0.3 g (38%) 6-*exo*-methylbicyclo[3.1.0]hex-2-en-6-*endo*-carbinol **(24)**, b.p. 85–95°/11 Torr. The two oily products were identified by comparison of their NMR. spectra with those of authentic samples (see [6] and 5.2).

3.3. *Treatment of* 7-exo-*chloro*-7-endo-*methylbicyclo[3.2.0]hept-2-en-6*-exo-*ol* **(13)** (1.5 g, 9.5 mmol) with 2.9 g (10 mmol) tri-*n*-butyltin hydride gave 1.0 g (85%) 7-*endo*-methylbicyclo[3.2.0]hept-2-en-6-*exo*-ol **(21)** [11], b.p. 100–110°/11 Torr. – IR. (CCl_4): 3600–3300, OH. – NMR. (100 MHz in CCl_4): 5.71 (*s*, 2H, H–C(2), H–C(3)); 3.35 (*d*×*d*, *J* = ~5 and ~5, 1H, H–C(6)); 3.11 (*d*×*d*×*m*, *J* = ~9 and ~6, 1H, H–C(1)); 2.50 (*d*×*d*×*m*, *J* = ~6 and ~5, 1H, H–C(5)); 2.7–2.2 (*m*, 3H, H_2–C(4), H–C(7)); 0.97 (*s*, 3H, CH_3–C(7)).

3.4. *Treatment of* 7-exo-*bromo*-7-endo-*methylbicyclo[3.2.0]hept-2-en-6*-exo-*ol* **(14)** (0.6 g, 2.95 mmol) with 0.9 g (3.1 mmol) tri-*n*-butyltin hydride gave 0.3 g (82%) 7-*endo*-methylbicyclo[3.2.0]hept-2-en-6-*exo*-ol **(21)**, b.p. 100–110°/11 Torr; IR. and NMR. spectra identical with those described (3.3).

3.5. *Treatment of* 7-exo-*chloro*-7-endo-*phenylbicyclo[3.2.0]hept-2-en-6*-exo-*ol* **(15).** – 2.5 g (11.4 mmol) of crude **15** (60–70% pure, see 2.7.2) and 3.5 g (12 mmol) tri-*n*-butyltin hydride gave a crude product chromatographed on silica gel in benzene/ethyl acetate 95:5. Tri-*n*-butyltin hydride was eluted first. From later fractions a mixture (1.2 g, 7:3) of 7-*endo*-phenylbicyclo[3.2.0]hept-2-en-6-*exo*-ol **(20)** and 6-phenylbicyclo[3.1.0]hex-2-en-6-carbinol **(29)** was obtained. The latter compound was identified by comparison of the NMR. spectrum of the mixture with that of pure **29** obtained by vigorous $LiAlH_4$ reduction of **12** (see 5.3). The remaining signals in the spectrum were assigned to 7-*endo*-phenylbicyclo[3.2.0]hept-2-en-6-*exo*-ol **(20).** – NMR. (100 MHz in $CDCl_3$): 5.71 and 5.55 (2*m*, 2H, H–C(3), H–C(2)); 4.12 (*m*, 1H, H–C(6));

3.47 (*m*, 2H, H–C(1), OH); 2.69 (*m*, 1H, H–C(5)); 2.6-2.2 (*m*, 2H, H_2–C(4)). The alcohol **20** could not be obtained pure.

4. Rearrangements of 7-halobicyclo[3.2.0]hept-2-en-6-ols by base. – 4.1. *With aqueous sodium hydroxide.* The 7-halobicyclo[3.2.0]hept-2-en-6-ol (1 mol equivalent) was stirred with 1N NaOH solution (1.2-2 mol equivalents) at RT. for 60-120 min. The organic material was extracted into ether and the combined ether extracts were dried (Na_2SO_4) and concentrated. The residue was distilled under reduced pressure.

4.1.1. *Treatment of* 7-endo-*chlorobicyclo[3.2.0]hept-2-en-6*-endo-*ol* (**5**) *and its 7-deuterio derivative* **6.** For treatment of **5** see [7]. From 2.00 g (13.7 mmol) of 7-*exo*-deuterio-7-*endo*-chlorobicyclo[3.2.0]hept-2-en-6-*endo*-ol (**6**) and 35 ml 1N NaOH, 1.10 g (73%) of a colourless oil, b.p. 80–90°/40 Torr, was obtained as a 7:3 valence tautomeric mixture of 6-exo-*deuteriobicyclo[3.1.0]hex-2-ene-6*-endo-*carbaldehyde* (**27**, R=D) and *4-deuterio-2-oxabicyclo[3.2.1]octa-3,6-diene* (**30**, R=D). The NMR. spectrum was identical with the mixture of the corresponding 6- and 4-protio derivatives (**27** and **30**) [15] except that the signals at 1.59 (H–C(6)) of **27**, and at 4.93 (H–C(4)) of **30** were missing, and that the CHO signal at 9.07 of **27** and the H–C(3) signal at 5.73 of **30** had lost a coupling of 6 and 7 Hz, respectively.

4.1.2. *Treatment of* 7-endo-*chloro*-7-exo-*methylbicyclo[3.2.0]hept-2-en-6*-endo-*ol* (**7**). [7].

4.1.3. *Treatment of* 7-endo-*bromo*-7-exo-*methylbicyclo[3.2.0]hept-2-en-6*-endo-*ol* (**8**) (0.25 g, 1.24 mmol) with 2.5 ml 1N NaOH gave, after 60 min, 0.1 g (66%) of a mixture of 6-*exo*-methylbicyclo[3.1.0]-hex-2-ene-6-*endo*-carbaldehyde and its valence tautomer 4-methyl-2-oxabicyclo[3.2.1]octa-3,6-diene (**26** ⇄ **31**, 4:1), b.p. 80–90°/20 Torr (bulb tube). NMR. spectrum identical with that described [7].

4.1.4. *Treatment of* 7-exo-*chloro*-7-endo-*methylbicyclo[3.2.0]hept-2-en-6*-exo-*ol* (**13**). – 4.1.4.1. *With cold aqueous NaOH.* – 3.17 g (20 mmol) **13** and 30 ml 1N NaOH gave after 70 min 1.76 g (72%) of a mixture (GC.-B) consisting of 7-*exo*- (**32**) and 7-*endo*-methylbicyclo[3.2.0]hept-2-en-6-one (**23**) (1:2), b.p. 80–90°/11 Torr (bulb tube). The products were identified by comparison with pure samples (GC.-B and NMR.) (see 4.1.4.2).

4.1.4.2. *With hot aqueous NaOH.* A solution of 3.40 g (21.4 mmol) **13** in 3 ml ethanol was added during 10 min to 30 ml boiling 1N aqueous NaOH. The reaction product was distilled as formed by passing steam through the mixture. The distillate was extracted 3 times with ether. The combined ether extracts were dried (Na_2SO_4), evaporated and distilled, b.p. 80–90°/11 Torr (bulb tube), to give 2.23 g (85%) of a mixture containing (GC.-B) 45% **32** and 55% **23** separated by preparative GC.-C. The first compound eluted (45%) was 7-*exo*-methylbicyclo[3.2.0]hept-2-en-6-one (**32**). – NMR. (100 MHz in CCl_4): 5.83 and 5.73 (2*m*, 2H, H–C(2), H–C(3)); 3.84 (*m*, 1H, H–C(5)); 2.99 (*m*, 1H, H–C(1)); 2.9-2.2 (*m*, 3H, H–C(7), H_2–C(4)); 1.24 (*d*, J = 8.0, 3H, CH_3–C(7)). The last component eluted (55%), 7-*endo*-methylbicyclo[3.2.0]hept-2-en-6-one (**23**), was identical (NMR.) with an authentic sample [6] [16].

4.1.4.3. *With NaOD in D_2O.* 1.00 g (6.3 mmol) **13** and 10 ml 1N NaOD in D_2O gave, after 30 min (intentionally incomplete reaction), 0.5 g of a mixture which contained (by comparison of the CH_3-signals in the NMR. spectrum with those of authentic samples) 30% starting material (**13**, δ = 1.50, *s*), 40% of the non-deuterated *exo*-isomer, 7-*exo*-methyl-7-*endo*-protio- (**32**, δ = 1.23, *d*, J = 8) and 30% of the deuterated *endo*-isomer, 7-*endo*-methyl-7-*exo*-deuteriobicyclo[3.2.0]hept-2-en-6-one (**34**, δ = 0.99, *s*).

4.1.5. *Treatment of* 7-exo-*bromo*-7-endo-*methylbicyclo[3.2.0]hept-2-en-6*-exo-*ol* (**14**) (0.3 g, 1.5 mmol) with 1 ml 1N NaOH yielded, after 60 min, 0.15 g (83%) of a mixture (3:7) of 7-*exo*- (**32**) and 7-*endo*-methylbicyclo[3.2.0]hept-2-en-6-one (**23**) b.p. 80–90°/11 Torr (bulb tube). The products were identified by comparison of the NMR. spectrum of the mixture with those of pure samples (see 4.1.4.2).

4.1.6. *Treatment of* 7-exo-*chloro*-7-endo-*phenylbicyclo[3.2.0]hept-2-en-6*-exo-*ol* (**15**). A mixture of 2.60 g (~ 10 mmol) of crude **15** (containing 60–70% of **15**, see 2.7.2) and 20 ml 1N NaOH afforded, after 30 min, 0.98 g (~ 50%) of a yellow oil, b.p. 110°/0.1 Torr (bulb tube), which consisted of 7-*exo*-phenyl- (**33**) and 7-*endo*-phenylbicyclo[3.2.0]hept-2-en-6-one (**22**) (*ca.* 4:6). The two products were identified by comparison of the NMR. spectrum of the mixture with spectra of the pure epimers [14] [6].

4.2. *Treatment with conc. KOH solution.* – The chloroalcohol was added to a solution of KOH (5 g) in water (15 ml) and the mixture was mechanically shaken for 2 min. Extraction with dichloromethane yielded the crude rearrangement product purified by bulb tube distillation.

4.2.1. *Treatment of* 7-endo-*chlorobicyclo[3.2.0]hept-2-en-6*-endo-*ol* (**5**) (300 mg) gave 195 mg (87%) of the valence tautomeric mixture (**27** ⇄ **30**) (cf. 4.1.1).

4.2.2. *Treatment of* 7-endo-*chloro*-7-exo-*methylbicyclo[3.2.0]hept-2-en-6*-endo-*ol* (**7**) (200 mg) gave 150 mg (91%) of the valence tautomers (**26** ⇄ **31**) as a colourless oil (cf. [7]).

4.2.3. *Treatment of* 7-exo-*chloro*-7-endo-*methylbicyclo[3.2.0]hept-2-en-6*-exo-*ol* **(13)** (100 mg) gave 71 mg (87%) of the equilibrium mixture of 7-*exo*- and 7-*endo*-methylbicyclo[3.2.0]hept-2-en-6-ones (**32** and **23**).

4.2.4. *Treatment of* 7-exo-*chloro*-7-endo-*methylbicyclo[3.2.0]hept-2-en-6*-endo-*ol* **(16)** (91% pure, 110 mg) gave 79 mg (96%) 6-*endo*-methylbicyclo[3.1.0]hex-2-en-6-*exo*-carbaldehyde (**35**). – IR. (CCl_4): 2730, 1707, CHO. – NMR. (60 MHz in $CDCl_3$): 8.97 (*s*, 1H, CHO); 5.83–5.56 (*m*, 2H, H–C(2), H–C(3)); 2.69–1.90 (*m*, 4H, H–C(1), H–C(5) and H_2–C(4)); 0.98 (*s*, 3H, CH_3–C(6)). Semicarbazone, m.p. 190–193° (preheated block). Signals due to the products **23** and **32** from the rearrangement of the 9% of 6-*exo*-alcohol **13**, present as impurity in the starting material, were noted in the IR. (1770 cm^{-1}) and in the NMR. spectra.

4.2.5. *Treatment of* 7-exo-*chloro*-7-endo-*methylbicyclo[3.2.0]hept-2-en-6*-exo-*ol* **(13)** with NaOD–D_2O. – The chloroalcohol **13** (500 mg) was shaken mechanically with NaOD–D_2O (1.9 g Na in 10 ml D_2O) for 1 min. Extraction with dichloromethane gave a mixture of unchanged chloroalcohol **13**, 1.59 (*s*, CH_3–C(7)), and of the two rearranged cyclobutanones, 7-*exo*-methyl-7-*endo*-protiobicycloheptenone **32**, 1.25 (*d*, CH_3–C(7)), and 7-*endo*-methyl-7-*exo*-deuterioketone **34**, 0.98 (*s*, CH_3–C(7)). The ratio of **13:32:34** was 69:8:23.

4.3. *With sodium methylsulfinyl carbanion in dimethylsulfoxide (DMSO).* – To a stirred ice-cooled solution of 1 mol equivalent of the 7-chlorobicyclo[3.2.0]hept-2-en-6-ol in DMSO was added dropwise a 0.4 or 2.3 molar solution of 1.1 mol equivalent of sodium methylsulfinyl carbanion in DMSO [26]. The reaction mixture was stirred for 60 min at RT., diluted with ether and washed 5 times with water. The ether layer was dried (Na_2SO_4), concentrated and the residue distilled (bulb tube) under reduced pressure.

4.3.1. *Treatment of* 7-endo-*chloro*-7-exo-*methylbicyclo[3.2.0]hept-2-en-6*-endo-*ol* **(7)** (1.00 g, 6.3 mmol) in 10 ml DMSO in this way with 6.9 mmol sodium methylsulfinyl carbanion in 17 ml DMSO yielded 0.40 g (53%) of a mixture of 6-*exo*-methylbicyclo[3.1.0]hex-2-ene-6-*endo*-carbaldehyde and its valence tautomer 4-methyl-2-oxabicyclo[3.2.1]octa-3,6-diene (**26** ⇄ **31**, 4:1) b.p. 80–100°/20 Torr. The NMR. spectrum was identical with that described [7].

4.3.2. *Treatment of* 7-exo-*chloro*-7-endo-*methylbicyclo[3.2.0]hept-2-en-6*-exo-*ol* **(13)** (1.00 g, 6.3 mmol) in 10 ml DMSO with a solution of 17 ml DMSO containing 6.9 mmol sodium methylsulfinyl carbanion yielded 0.50 g (66%) of a mixture (GC.-B, 1:3) of 7-*exo*- and 7-*endo*-methylbicyclo[3.2.0]hept-2-en-6-ones (**32** and **23**), b.p. 100°/15 Torr.

4.4. *Treatment of* 7-endo-*chlorobicyclo[3.2.0]hept-2-en-6*-endo-*ol* **(5)** *with sodium hydride in ether.* To a stirred and cooled (–10°) suspension of 1.25 g (52 mmol) NaH in 20 ml ether was added during 30 min a solution of 7.23 g (50 mmol) 7-*endo*-chlorobicyclo[3.2.0]hept-2-en-6-*endo*-ol **(5)** in 20 ml ether. After standing for 120 min at RT., the mixture was filtered and the filtrate concentrated. Distillation (bulb tube) at 80–90°/40 Torr gave 3.26 g (60%) of a mixture of bicyclo[3.1.0]hex-2-ene-6-*endo*-carbaldehyde and its valence tautomer 2-oxabicyclo[3.2.1]octa-3,6-diene (**27** ⇄ **30**, 7:3), identical (NMR.) with that reported [7] [15].

5. Reductive rearrangement of 7-*endo*-halobicyclo[3.2.0]hept-2-en-6-ones with lithium aluminium hydride. – 5.1. *Bicyclo[3.1.0]hex-2-en-6*-endo-*carbinol* **(25)**. To a stirred and ice-cooled suspension of 2.50 g (66 mmol) $LiAlH_4$ in 50 ml tetrahydrofuran (THF) was added dropwise a solution of 7.23 g (50 mmol) 7-*endo*-chlorobicyclo[3.2.0]hept-2-en-6-one **(1)** [3] [6] [7] [21] in 20 ml THF. After refluxing for 44 h, water was added carefully, then 10% hydrochloric acid. The reaction mixture was extracted 5 times with ether; the ether extracts were dried (Na_2SO_4), evaporated, and the residue distilled, b.p. 80–90°/11 Torr (bulb tube), 3.75 g (68%), >95% pure (GC.-D), bicyclo[3.1.0]hex-2-ene-6-*endo*-carbinol (**25**), identical (NMR.) with an authentic sample [18].

5.2. 6-exo-*Methylbicyclo[3.1.0]hex-2-ene-6*-endo-*carbinol* **(24)**. 2.00 g (16.6 mmol) 7-*endo*-chloro-7-*exo*-methylbicyclo[3.2.0]hept-2-en-6-one **(3)** [6] [22] [23] reacted with 0.60 g (15.8 mmol) $LiAlH_4$ in 25 ml THF as in 5.1 to yield 1.02 g (65%) solid 6-*exo*-methylbicyclo[3.1.0]hex-2-en-6-*endo*-carbinol **(24)**. Recrystallization from pentane at –20° gave an analytical sample, m.p. 31.5–32.5°. – IR. (CCl_4): 3620 and 3410, OH. – NMR. (100 MHz in CCl_4): 5.65 and 5.51 (2*m*, 2H, H–C(2), H–C(3)); 3.3 (*s*, 1H, OH); 3.25 (*s*, 2H, CH_2–C(6)); 2.47 (*d*×*d*, *J* = 18.2 and 7.5, 1H, *exo*-H–C(4)); 2.11 (*d*×*m*, *J* = 18.2, 1H, *endo*-H–C(4)); 1.74 (*d*×*m*, *J* = ~6, 1H, H–C(1)); 1.37 (*d*×*d*×*d*, *J* = 7.5, 6 and ~2, 1H, H–C(5)); 1.09 (*s*, 3H, CH_3–C(6)).

5.3. *6-Phenylbicyclo[3.1.0]hex-2-en-6-carbinol* **(29)**. A suspension of 2.0 g (9.2 mmol) 7-*exo*-chloro-7-*endo*-phenylbicyclo[3.2.0]hept-2-en-6-one **(12)** [6] [25] and 0.5 g (13 mmol) $LiAlH_4$ in 80 ml ether was

refluxed for 6 h. Water and dilute H_2SO_4 were added and the reaction mixture was extracted twice with ether; the ether extracts were dried (Na_2SO_4) and evaporated. The residue was chromatographed on silica gel in ethyl acetate/benzene 5:95 to give 0.35 g (20%) 7-*endo*-phenylbicyclo[3.2.0]hept-2-en-6-*endo*-ol (**18**) (NMR. see 2.8) and 0.75 g (44%) 6-phenylbicyclo[3.1.0]hex-2-en-6-carbinol (**29**), b.p. 142°/0.07 Torr. – NMR. of **29** (100 MHz in CCl_4): 7.45–7.00 (*m*, 5H, ArH); 5.80 and 5.61 (2*m*, 2H, H–C(2), H–C(3)); 3.43 (*s*, 2H, CH_2–C(6)); 2.96 (*s*, 1H, OH); 2.60–1.67 (*m*, 4H, H–C(1), H_2–C(4), H–C(5)).

6. Lithium aluminium hydride reduction of the valence tautomeric mixture of 6-*exo*-methylbicyclo[3.1.0]hex-2-en-6-*endo*-carbaldehyde and 4-methyl-2-oxabicyclo[3.2.1]octa-3,6-diene (26⇄31). To a stirred suspension of 0.5 g (13.2 mmol) $LiAlH_4$ in 50 ml ether was added dropwise a solution of 1.0 g (8.2 mmol) valence tautomeric mixture (**26⇄31**). After stirring for 4 h at RT., water was added carefully, then 10% hydrochloric acid. The ether layer was separated and the aqueous phase was extracted 3 times with ether. The combined ether fractions were dried (Na_2SO_4) and evaporated. Bulb tube distillation of the residue gave 0.65 g (63%) 6-*exo*-methylbicyclo[3.1.0]hex-2-en-6-*endo*-carbinol (**24**), b.p. 105°/11 Torr, NMR. and IR. spectra identical to those described (5.2).

7. Acid-catalysed rearrangement of 7-*exo*-chloro-7-*endo*-phenylbicyclo[3.2.0]hept-2-en-6-*exo*-ol (15). – 7.1. *With 4N aqueous hydrochloric acid.* 0.8 g (3.6 mmol) crude **15** (60–70% of **15**, see 2.7.2) was stirred with 38 ml 4N aqueous HCl for 1 h at RT. The suspension was extracted with ether and the combined ether extracts evaporated. The residue was distilled to give 0.3 g (45%) 4-phenyl-2-oxabicyclo[3.3.0]octa-3,7-diene (**38**), b.p. 125–130°/0.25 Torr (bulb tube). – NMR. (100 MHz in CCl_4): 7.07 (*m*, 5H, ArH); 6.57 (*d*, J = 1.8, 1H, H–C(3)); 5.90–5.40 (*m*, 3H, H–C(1), H–C(7), H–C(8)); 3.8 (*m*, 1H, H–C(5)); 2.7–2.4 (*m*, 2H, H_2–C(6)).

7.2. *With aqueous silver nitrate.* 1.0 g (4.5 mmol) of crude **15** (from 2.7.2) was stirred with 2.5 g $AgNO_3$ in 40 ml water for 1 h at RT. The suspension was filtered and the filtrate extracted with ether. The combined ether extracts were dried, evaporated and the residue distilled, b.p. 125–130°/0.25 Torr (bulb tube) to give 0.25 g (30%) 4-phenyl-2-oxabicyclo[3.3.0]octa-3,7-diene (**38**), NMR. spectrum identical with that described (7.1).

7.3. *With silica gel.* – 4.0 g (18 mmol) of crude **15** (from 2.7.2) was passed through a silica gel column with hexane/benzene 1:2. The top one-third of the column was observed to darken slowly while 1.6 g (48%) 4-phenyl-2-oxabicyclo[3.3.0]octa-3,7-diene (**38**) was eluted; NMR. spectrum identical to that described (7.1).

8. Reaction of methylmagnesium iodide with 7-halobicyclo[3.2.0]hept-2-en-6-ones. – 8.1. *Treatment of* 7-endo-*chlorobicyclo[3.2.0]hept-2-en-6-one* (**1**). – An ethereal solution of CH_3MgI (1.54M, 56 ml) was added over 2 min to the monochloroketone **1** (12 g) in ether at 0°. After one further min the mixture was poured into saturated NH_4Cl solution. The ether layer was washed with brine and the residue from the ethereal solution distilled to yield 7-*endo*-chloro-6-*exo*-methylbicyclo[3.2.0]hept-2-en-6-*endo*-ol (**41**) (oil, 9.35 g), b.p. 51–53°/0.5 Torr. For analysis, traces of the ketone **11** were removed by chromatography on silica gel in benzene. – IR. (CCl_4): 3545 OH. – NMR. (60 MHz in $CDCl_3$): 5.87 (*m*, 2H, H–C(2), H–C(3)); 4.43 (*d*, J = 7, 1H, H–C(7)); 3.55 (*m*, 1H, H–C(5)); 2.80 (*m*, 1H, H–C(1)); 2.52 (*m*, 2H, H_2–C(4)); 1.25 (*s*, 3H, CH_3–C(6)); 2.05 (*s*, 1H, OH).

8.2. *Treatment of* 7-exo-*chloro-7*-endo-*methylbicyclo[3.2.0]hept-2-en-6-one* (**10**). A solution of CH_3MgI (11 mmol) in ether (50 ml) was added over 5 min to a solution of the *exo*-chloro-*endo*-methylketone **10** (1.56 g, 10 mmol) in dry ether (50 ml). The solution was stirred for 30 min and poured into iced 10% sulfuric acid. Ether extraction yielded an oil which was chromatographed in benzene to give first 0.78 g (50%) of **10**, then 0.45 g (66% based on reacted ketone) of 6-*exo*-acetyl-6-*endo*-methylbicyclo[3.1.0]hex-2-ene (**46**), b.p. 120°/11 Torr (bulb tube). – IR. (CCl_4): 1690 C=O. – NMR. (100 MHz in CCl_4): 5.67 (*m*, 2H, H–C(2), H–(3)); 2.7–2.0 (*m*, 4H, H–C(1), H_2–C(4), H–C(5)); 2.12 (*s*, 3H, $COCH_3$); 1.01 (*s*, 3H, CH_3–C(6)).

9. Treatment of 7-*endo*-chloro-6-*exo*-methylbicyclo[3.2.0]hept-2-en-6-*endo*-ol (41) with base. – The *endo*-alcohol **41** (9.0 g) was mechanically shaken with a strong aqueous solution of KOH (150 g in 150 ml H_2O) for 30 min. The mixture was poured into brine and extracted with dichloromethane (3 × 100 ml). The organic extracts were washed with brine and dried. Concentration and distillation gave 6.1 g (88%) of the valence tautomeric mixture of 6-*endo*-acetylbicyclo[3.1.0]hex-2-ene and 3-methyl-2-oxabicyclo[3.2.1]octa-3,6-diene (**44⇄45**), b.p. 94–97°/23 Torr. – IR. (CCl_4): 1700 C=O. –

NMR. (60 MHz in $CDCl_3$): 6.33 (*m*, H–C(6), H–C(7) of **45**); 5.57 (*m*, H–C(2), H–C(3) of **44**); 4.75 (*m*, H–C(4) of **45**); 2.03 (*s*, CH_3CO of **44**); 1.53 (*d*, CH_3–C(3) of **45**). From the relative intensities of the methyl signals at 2.03 and 1.53, the mixture contained $92 \pm 3\%$ of ketone **44**. – MS.: M^+ 122.07319 (theory 122.07316).

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