214. Fragmentation of Homoallylic Alkoxides. Thermolysis of Potassium 2-Substituted Bicyclo[2.2.2]oct-5-en-2-alkoxides

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Summary

Thermolysis of the potassium 2-substituted bicyclo[2.2.2]oct-5-en-2-alkoxides derived from alcohols **2**–**17** at 90–120° in hexamethylphosphoric triamide affords unsaturated ketones resulting from allylic bond cleavage. The mechanistic and synthetic aspects of this anionic fragmentation are discussed with reference to the formation of 1-(3′-cyclohexenyl)-2-alkanones **18**–**28** *via* initial heterolytic C(1),C(2)-bond cleavage in the substrate alkoxide and regioselective, intramolecular protonation of the resultant transient allylic anion.

Introduction. – The thermolysis of a homoallylic alcohol to give an alkene and a carbonyl compound (*Scheme 1*, M = H) is well documented[1]). Synthetic use of this reaction is, however, limited by the generally high temperatures required (> 200°) and the stereochemical necessity for a *syn*-relationship between the hydroxyl group and the olefinic double bond. Conversely, the fragmentation of a homoallylic metal alkoxide occurs at a substantially lower temperature and leads to the formation of an alkene and a metal enolate (*Scheme 1*, M = metal)[2]). This reaction involves reversible cleavage of the allylic bond followed by enolatization of the resulting ketone by either the transient organometallic species or the alkoxide substrate[3]). Although the first step is believed to be concerted when the metal is magnesium (M = MgCl, MgBr) [5] little is known about the reaction mechanism for more electropositive metals such as sodium or potassium (M = Na, K). In addition, the synthetic aspects of this anionic fragmentation reaction have never been systematically studied[4]). We now describe the thermolysis of a series of potassium 2-substituted bicyclo[2.2.2]oct-5-en-2-alkoxides.

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[1]) This fragmentation, also termed the β-hydroxy-olefin cleavage, represents an example of the *retro*-ene reaction [1] [2].

[2]) This fragmentation is observed as a side reaction during the thermal rearrangement of homoallylic tertiary alkoxides (M = Li, MgCl, MgBr) [3] and in competition with the anionic *oxy-Cope* rearrangment (M = Na, K) [4].

[3]) Because enolatization of carbonyl groups by allylic organometallic species had never been observed, enolatization by the alkoxide substrate was considered to be more likely [3].

[4]) Only a few synthetic applications are known and involve the opening of appropriately substituted cyclobutoxides [6].

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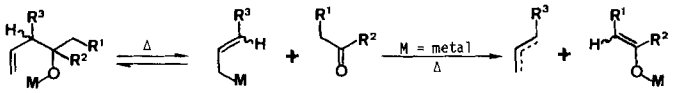
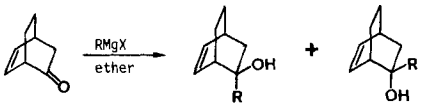
Scheme 1



Results and discussion. – Treatment of bicyclo[2.2.2]oct-5-en-2-one (**1**) with the appropriate *Grignard* reagent afforded a series of 2-substituted bicyclo[2.2.2]oct-5-en-2-ols, **2**–**17**, which were separated by column chromatography into their respective *exo*- and *endo*-epimers[5][6] *(Scheme 2)*. Addition of these epimerically pure alcohols[7] to a slurry of a slight excess of potassium hydride (1.1 mol-equiv.) in hexamethylphosphoric triamide (HMPA) at 10° under an inert atmosphere afforded the corresponding potassium alkoxides which, without isolation, were heated in the same solvent at 90–120° during 1–2 h prior to a standard aqueous work-up. For the majority of the substrates examined the formation of an unsaturated ketone *via* allylic bond cleavage is the principal reaction pathway *(cf. Table)*.

Scheme 2



	exo	R =	*endo*
1	**2**	Me	**3**
	4	Et	**5**
	6	Pr	**7**
	8	*iso*-Pr	**9**
	10	$CH_2CH{=}CH_2$	**11**
	12	$CH_2C(Me){=}CH_2$	**13**
	14	CH_2Ph	**15**
	16	Ph	**17**

Thermolysis at 120° of the potassium alkoxides derived from the 2-methyl, 2-ethyl, 2-propyl and 2-isopropyl bicyclic alcohols **2**–**9** led to the isolation, in good yield, of the 3-cyclohexenyl ketones **18**–**21**, together with small amounts (*ca.* 10%) of their 2-cyclohexenyl isomers (*cf.* experiments 1–6). In addition to the fact that epimeric alkoxides give the same product two observations are worthy of mention. Firstly there is only partial epimerization of the substrate alkoxide during the reaction and, secondly, the *exo*-alkoxide reacts noticeably faster than its *endo*-epimer. These results are consistent with a reaction mechanism in which the rate-

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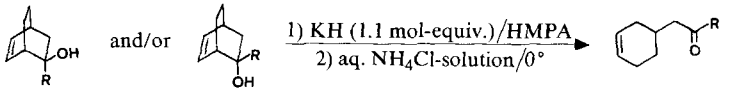
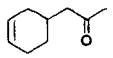
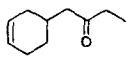
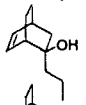
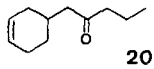
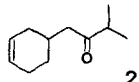
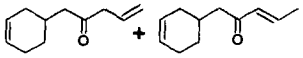
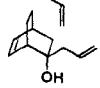
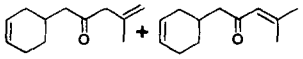
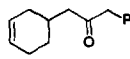
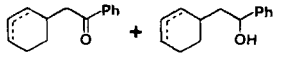
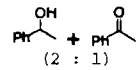
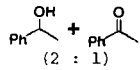
[5]) *Exo* and *endo* define the stereochemistry of the hydroxyl group relative to the cyclic double bond.

[6]) The less polar *exo*-epimer is almost invariably the major product, indicating that the *Grignard* reagent preferentially attacks the sterically less encumbered *endo*-face of **1**; for a related example of *endo*-selectivity see [7].

[7]) Two epimeric pairs of alcohols, **4**, **5** and **8**, **9**, were not cleanly separable by column chromatography. The epimeric mixtures (*exo*/*endo* 3:1) were therefore used as substrates for the subsequent thermolyses (*cf.* experiments 3 and 6, *Table*).

Table

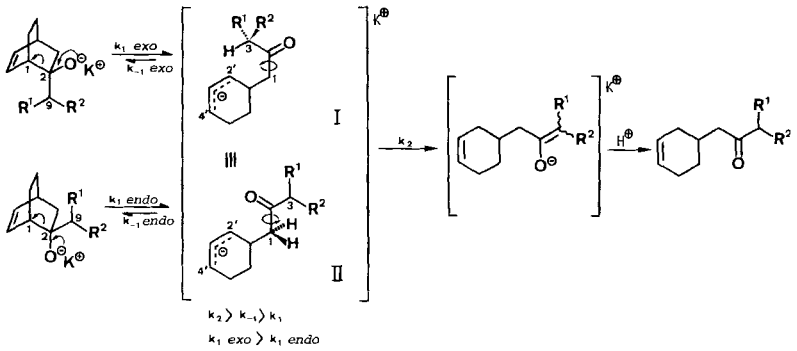


Exper.	Substrate[a][b]	Reaction conditions	Cyclohexene products[c]	Yield[d] %	Other products[c]	Yield[d] %
1	 **2**	120°/2 h	 **18**[f]	68		
2	 **3**	120°/2 h	**18**[f]	52		
3	 **4+5**[e]	120°/2 h	 **19**[f]	70		
4	 **6**	120°/2 h	 **20**[f]	67		
5	 **7**	120°/2 h	**20**[f]	51		
6	 **8+9**[e]	120°/2 h	 **21**[f]	64		
7	 **10**	90°/2 h	 **22** (4 : 1) **23**	74		
8	 **11**	90°/2 h	**22** + **23** (4 : 1)	<10	**1** + PhOH (3 : 1)	65
9	 **12**	90°/2 h	 **24** (4 : 1) **25**	76		
10	 **13**	90°/2 h	**24** + **25** (4 : 1)	<10	**1** + PhOH (3 : 1)	61
11	 **14**	90°/2 h	 **26**	54		
12	 **15**	90°/2 h	**26**	<5	**1** + PhOH (3 : 1)	68
13	 **16**	90°/1 h	 **27**, **28**[g] (1 : 3) **29**, **30**[g,h]	8	 (2 : 1)	45
14	 **17**	90°/1 h	**27**, **28**[g] + **29**, **30**[g,h]	6	 (2 : 1)	48

[a]) Substrate in experiments 1, 3, 4, 6, 7 and 9 was 10 mmol; in experiments 2, 5, 8, 10, 11, 12, 13 and 14, 1 mmol. [b]) Isomeric purity >95%. [c]) Structures confirmed by spectral data (IR. ^{1}H- and ^{13}C-NMR., and MS). [d]) Yields, not optimized, refer to distilled products. [e]) (3:1)-Mixture of *exo*- and *endo*-isomers. [f]) Contains *ca.* 10% 2-cyclohexenyl isomer. [g]) (30:70)-Mixture of 3- and 2-cyclohexenyl isomers. [h]) Diastereoisomeric mixture.

determining step is the heterolytic cleavage of the allylic C(1), C(2)-bond to form a transient allylic anion which is then irreversibly quenched by intramolecular capture of a proton adjacent to the carbonyl group[8]). The resulting potassium enolate subsequently affords the 3-cyclohexenyl ketone by external protonation[9]) *(Scheme 3)*. The high selectivity (*ca.* 90%) with respect to the position of the cyclohexenyl double bond may be rationalized by the strong preference for intramolecular proton transfer from the C(3)-position to the C(2′)-position of the allylic anion *via*

Scheme 3



the six-membered transition state provided by conformation I[10]). To our knowledge this is the first example of an allylic anion which reacts with a ketone preferentially as a base rather than as a nucleophile (*cf.* footnote 3). Intermolecular proton transfer would be expected neither to be regioselective nor to compete favourably with intramolecular attack of the allylic anion on the carbonyl group, *i.e.* epimerization of the substrate alkoxide. The observed rate difference between *exo*- and *endo*-epimeric alkoxides is possibly the result of a stabilization of the C(1), C(2)-bond in the *endo*-alkoxide caused by electron donation from the O-anion to the cyclic double bond.

The thermolysis of the potassium alkoxides prepared from the 2-allyl, 2-(2-methallyl) and 2-benzyl substituted alcohols **10**–**15** were performed at 90°. In contrast with the 2-alkyl substituted alkoxides the reaction products from these epimeric alkoxides are now dependent on the substrate stereochemistry. The *exo*-alkoxides afforded in good yield exclusively the 3-cyclohexenyl ketones **22** and **23**, **24** and **25** ((4:1)-mixtures of the β,γ- and α,β-unsaturated ketones) and **26**

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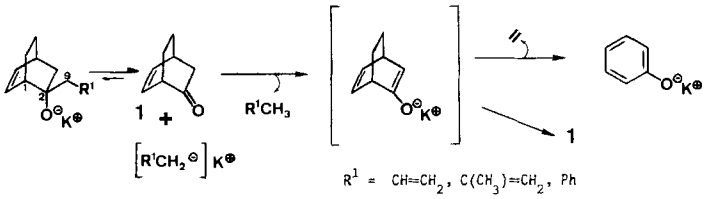
[8]) Quenching the reaction with deuterium oxide did not lead to an observable deuterium incorporation into the cyclohexene ring (MS. analysis). This result is consistent with a rapid intramolecular proton transfer.

[9]) Under the reaction conditions the potassium enolate degenerates to its parent ketone, presumably by proton transfer from the solvent. For example, the potassium enolates of **18** decompose with a half-life of *ca.* 8 h at 25°; at 120° the decomposition is essentially complete after 2 h (*cf.* exper. part).

[10]) This kinetic explanation, as opposed to a thermodynamic argument, is supported by the fact that the 3-cyclohexenyl ketone is isomerized to a (3:1)-mixture of the 3- and 2-cyclohexenyl ketones under strongly basic conditions (*cf.* exper. part).

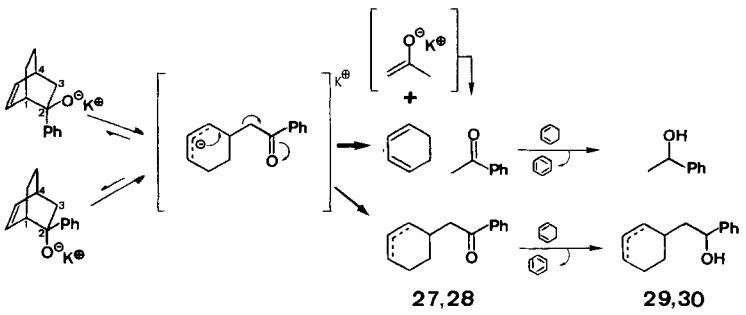
Scheme 4



via C(1), C(2)-bond cleavage (*cf.* experiments 7, 9 and 11). In contrast, the *endo*-alkoxides afforded **1** with loss of the C(2)-substituent by selective C(2), C(9)-bond cleavage and only small amounts of products (< 10%) resulting from C(1), C(2)-bond cleavage were observed (*cf.* experiments 8, 10 and 12). Also isolated was phenol whose formation we believe is the result of an anionic *retro*-[4 + 2]-cycloaddition of the potassium enolate of **1** with expulsion of ethylene[11]) *(Scheme 4)*. This marked difference between the *exo*- and *endo*-alkoxides may be due to a strengthening of the C(1), C(2)-bond in the *endo*-alkoxide caused by selective electron donation from the O-anion to the structurally rigid, cyclic double bond. In the *exo*-alkoxide the C(2), C(9)-bond may be stabilized by a similar electron donation from the O-anion to the double bond in the C(2)-substituent.

The thermolyses of the potassium alkoxides prepared from the 2-phenyl substituted bicyclic alcohols **16** and **17** were also effected at 90°. Both the *exo*- and *endo*-epimers afforded a (2:1)-mixture of 1-phenylethanol and acetophenone as the major products (45% and 48%) together with a (1:3)-mixture (6% and 8%) of the 3- and 2-cyclohexenyl ketones **27** and **28**, and the diastereoisomeric 3- and 2-cyclohexenyl alcohols **29** and **30**[12]) (*cf.* experiments 13 and 14). The formation of acetophenone is the result of two successive cleavages of the C(1), C(2)- and C(3), C(4)-bonds in the substrate to give 1,3-cyclohexadiene and the potassium enolate of acetophenone whose stability probably provides the driving force of this formal *retro-Diels-Alder* reaction *(Scheme 5)*.

Scheme 5



[11]) For a related example of an anionic *retro*-[4 + 2]-cycloaddition see [8].

[12]) No traces of products resulting from [1,3]- or [3,3]-sigmatropic shifts were observed.

The formation of **27** and **28** is the minor reaction pathway and, after C(1), C(2)-bond cleavage in the substrate alkoxide, intramolecular protonation is forced to take place from the C(1)-position of conformations I and II *(cf. Scheme 3)*. The observed 30:70 product ratio for the 3- and 2-cyclohexenyl isomers thus to take place from the C(1)-position, *i.e. via* conformation II *(cf. Scheme 3)*. position of the transient allylic anion[13]). The presence of 1-phenylethanol and the alcohols **29** and **30** is presumably due to a reduction of acetophenone and ketones **27** and **28** by a hydride transfer from 1,3-cyclohexadiene.

In conclusion, we have demonstrated that, in a rigid bicyclic system, the fragmentation of potassium homoallylic alkoxides may be used as a convenient synthetic alternative to the thermal *retro*-ene reaction of homoallylic alcohols. Two important advantages are the lower reaction temperatures and, as a direct consequence of the non-concerted nature of the reaction, the non-dependence on a *syn* relationship between the O-anion and the double bond. Further investigations concerning the synthetic limitations and scope of this fragmentation are at present under study.

We thank Mr. *W. Thommen* for assistance in the interpretation of the NMR. spectral data and Miss *B. Frei* for performing the capillary column GC. analyses. Technical assistance from Mr. *M. Wust* is also gratefully acknowledged.

Experimental Part

1. General. – All solvents were dried and distilled before use. Each reaction was followed by TLC. and GC. analysis. Work-up refers to: successive washing of the combined organic phase with H_2O, sat. aq. $NaHCO_3$-solution and sat. aq. NaCl-solution, drying of the organic phase (anhydrous Na_2SO_4) and removal of the solvent *i.v.* Thin layer chromatography (TLC.) with dichloromethane as eluent was performed using *Merck* 0.25 mm *(60 F 254)* silica gel plates. Preparative chromatography (column) was carried out on silica gel (*Merck*, 0.06–0.20 mm). Gas chromatograms (GC.): 4 atm N_2; glass columns (3 mm ID, 3 m), stationary phase on *Chromosorb W* (acid washed, 80/100 mesh): *5% Carbowax*, column temp. 200° unless otherwise stated, retention time in min. Capillary column: 0.7 atm He; *UCON* (52 m). Melting points (m.p.) are uncorrected. Boiling points (b.p.), using a bulb-to-bulb apparatus, refer to the oven temperature (bath) and pressure (Torr). IR. (*Perkin-Elmer A21* Spectrometer) spectra: liquid film unless otherwise specified, ν max in cm^{-1}. NMR. spectra: in $CDCl_3$, internal standard tetramethylsilane ($\delta = 0$ ppm); abbreviations: s = singlet, d = doublet, t = triplet, *qa*-quadruplet, m = multiplet, br. = broad, J = spin-spin coupling constant (Hz). ^{1}H-NMR. at 60 MHz *(Varian A-60)* or 360 MHz *(Bruker WH 360)*, ^{13}C-NMR. at 90.5 MHz. Mass spectra (MS.) (*Atlas CH 4;* electron energy: 70 eV) signals are given in *m/z* (rel. %).

2. Preparation of bicyclo[2.2.2]oct-5-en-2-one (1). – A solution of 1,3-cyclohexadiene (48 g, 0.6 mol) and 2-chloroacrylonitrile (59.2 g, 0.68 mol) in 200 ml of toluene containing hydroquinone (0.5 g) was heated at 90° during 43 h in an autoclave. Concentration of the mixture and column chromatography (CH_2Cl_2) gave 2-chlorobicyclo[2.2.2]oct-5-ene-2-carbonitrile as an epimeric mixture (white crystals, 46.9 g, 47%). This mixture was dissolved in 100 ml of EtOH and added to a solution of KOH (47 g, 0.84 mol) in 750 ml of EtOH. The solution was refluxed for 2 h and cooled. Addition of 500 ml of H_2O was followed by neutralization with glacial acetic acid. Extraction (ether), work-up, column chromatography (cyclohexane/ethyl acetate 6:4) and sublimation *i.v.* gave **1** as a white, crystalline solid (16.1 g, 47%), m.p. 82–85° (lit. [9]: 84–86°). – TLC.: Rf 0.35. – GC.: 2.4. – IR. (in $CDCl_3$):

[13]) This product ratio may also be explained by a non-regioselective intermolecular proton transfer.

1725, 1620, 1410, 1360, 1210, 1155, 858. – ^{1}H-NMR.: 1.10–2.10 (6 H); 3.10 (*m*, 2 H); 6.33 (*m*, 2 H). – MS.: 122 (0, $C_8H_{10}O^+$), 108 (17), 91 (1.4), 79 (8), 145 (100), 51 (1.4), 39 (8).

3. Preparation of 2–17. – *General procedure.* The epimeric pairs of bicyclic alcohols: **2** and **3**, **4** and **5**, **6** and **7**, **8** and **9**, **16** and **17**, were prepared on a 25-mmol scale by the addition of an ethereal solution of **1** to a 10% excess of the methyl, ethyl, propyl, isopropyl and phenyl *Grignard* reagents (freshly-prepared from the appropriate alkyl/aryl halide and magnesium) in ether, followed by reflux during 1 h. Alcohols **10** and **11**, **12** and **13**, **14** and **15** were prepared using *Barbier* conditions (also on a 25-mmol scale), *i.e.* a solution of 2-allyl, 2-methallyl or benzyl chloride (10% excess) and **1** was added to a stirred slurry of magnesium in refluxing ether. After 1 h the mixture were poured into cold sat. aq. NH_4Cl-solution. Extraction (ether), work-up and column chromatography (cyclohexane/ethyl acetate) was followed by distillation *i.v.* Subsequent separation of the epimers was effected by column chromatography.

3.1. *Preparation of (1*RS,*2*SR,*4*RS*)- and (1*RS,*2*RS,*4*RS*)-2-methylbicyclo[2.2.2]oct-5-en-2-ol* (**2** *and* **3**. (4:1)-mixture). Yield 82%, b.p. (sublimation) 120–130° (bath)/0.05 Torr.

Data of **2**. M.p. 83–84°. – TLC.: Rf 0.26. – GC.: 2.05. – IR. (in $CDCl_3$): 3600, 3450 (br.), 3050, 2870, 1450, 1370, 1280, 850, 810. – ^{1}H-NMR. (+D_2O): 1.08 and 1.26 (*m*, 2 H); 1.18 (*s*, 3 H); 1.44 (*m*, 2 H); 1.60 (*m*, 1 H); 2.10 (*m*, 1 H); 2.31 (*m*, 1 H); 2.56 (*m*, 1 H); 6.21 (*m*, 2 H). – MS.: 138 (0.8, $C_9H_{14}O^+$), 95 (1), 81 (7), 80 (100), 79 (38), 59 (5).

Data of **3**. M.p. 61–63°. – TLC.: Rf 0.25. – GC.: 2.05. – IR. (in $CDCl_3$): 3450 (br.), 3050, 1450, 1060, 914, 860, 736, 700. – ^{1}H-NMR. (+D_2O): 1.20 (*m*, 2 H); 1.40 (*m*, 2 H); 1.34 (*s*, 3 H); 1.64 (*m*, 2 H); 2.50 (*m*, 1 H); 2.60 (*m*, 1 H); 6.35 (*m*, 2 H). – MS.: 138 (0.6, $C_9H_{14}O^+$), 95 (3), 81 (9), 80 (100), 79 (40), 59 (3).

3.2. *Preparation of (1*RS,*2*SR,*4*RS*)- and (1*RS,*2*RS,*4*RS*)-2-ethylbicyclo[2.2.2]oct-5-en-2-ol* (**4** *and* **5**, (3:1)-mixture). Yield 73%.

Data of **4**. B.p. 120–130° (bath)/0.05 Torr. – TLC.: Rf 0.28. – GC.: 2.3. – IR. (in $CDCl_3$): 3600, 3050, 2875, 1460, 1370, 980, 810, 690. – ^{1}H-NMR.: 0.88 (*t*, *J* = 7, 3 H); 0.80–2.60 (10 H); 1.50 (*s*, 1 H, D_2O addition removes this signal); 6.18 (*m*, 2 H). – ^{13}C-NMR.: 133.4*d*, 76.4*s*, 41.9*t*, 40.8*d*, 35.9*t*, 31.2*d*, 24.5*t*, 19.8*t*, 7.1*qa*. – MS.: 152 (0.7, $C_{10}H_{16}O^+$), 123 (1.3), 95 (4), 80 (100), 79 (27), 73 (7).

Data of **5**. B.p. 120–130° (bath)/0.05 Torr. – TLC.: Rf 0.27. – GC.: 2.7. – IR. (in $CDCl_3$): 3600, 3050, 2880, 1460, 1380, 660. – ^{1}H-NMR. (+D_2O): 0.89 (*t*, *J* = 7, 3 H); 0.90–2.70 (10 H); 6.31 (*m*, 2 H). – ^{13}C-NMR.: 136.1*d*, 132.4*d*, 76.1*s*, 45.3*t*, 40.3*d*, 32.8*t*, 31.1*d*, 23.9*t*, 21.0*t*, 8.0*qa*. – MS.: 152 (0.5, $C_{10}H_{16}O^+$), 123 (1), 95 (4), 81 (6), 80 (100), 79 (28), 73 (6).

3.3. *Preparation of (1*RS,*2*SR,*4*RS*)- and (1*RS,*2*RS,*4*RS*)-2-propylbicyclo[2.2.2]oct-5-en-2-ol* (**6** *and* **7**, (3:1)-mixture). Yield 43%.

Data of **6**. B.p. 130–140° (bath)/0.05 Torr. – TLC.: Rf 0.35. – GC.: 3.2. – IR.: 3420 (br.), 3050, 2870, 995, 960, 860, 700. – ^{1}H-NMR.: 0.67–2.12 (13 H); 1.37 (*s*, 1 H, D_2O addition removes this signal); 2.44 (*m*, 2 H); 6.15 (*m*, 2 H). – MS.: 166 (1.4, $C_{11}H_{18}O^+$), 123 (1.4), 95 (3), 87 (10), 80 (100), 79 (17).

Data of **7**. B.p. 130–140° (bath)/0.05 Torr. – TLC.: Rf 0.34. – GC.: 3.2 – IR. (in $CDCl_3$): 3460 (br.), 3050, 2950, 2880, 1260, 818. – ^{1}H-NMR.: 0.80–2.60 (15 H); 1.52 (*s*, 1 H, D_2O addition removes this signal); 6.23 (*m*, 2 H). – MS.: 166 (0.6, $C_{11}H_{18}O^+$), 123 (1), 95 (4), 87 (9), 80 (100), 79 (20).

3.4. *Preparation of (1*RS,*2*RS,*4*RS*)- and (1*RS,*2*SR,*4*RS*)-2-isopropylbicyclo[2.2.2]oct-5-en-2-ol* (**8** *and* **9**, (3:1)-mixture). Yield 34%, b.p. 120–130° (bath)/0.05 Torr. – TLC.: Rf 0.31. – GC.: 3.1. – IR.: 3470 (br.), 3050, 2870, 1470, 1370, 990, 958, 720, 696. – ^{1}H-NMR.: 0.84 (*d*×*d*, *J* = 7, 6 H); 0.90–2.10 (7 H); 1.22 (*s*, 1 H, D_2O addition removes this signal); 2.55 (*m*, 2 H); 6.15 and 6.33 (*m*, 2 H). – MS.: 166 (1.3, $C_{11}H_{18}O^+$), 123 (7), 95 (10), 87 (14), 80 (100), 79 (23).

3.5. *Preparation of (1*RS,*2*SR,*4*RS*)- and (1*RS,*2*RS,*4*RS*)-2-allylbicyclo[2.2.2]oct-5-en-2-ol* (**10** *and* **11**, (5:1)-mixture). Yield 73%.

Data of **10**. B.p. 130–140° (bath)/0.05 Torr. – TLC.: Rf 0.41. – GC.: 3.2. – IR.: 3420 (br.), 3050, 2870, 1640, 1370, 1000, 920, 818, 720. – ^{1}H-NMR.: 1.08 (*m*, 1 H); 1.27 (*m*, 1 H); 1.44 (*m*, 2 H); 1.60 (*s*, 1 H, D_2O addition removes this signal); 1.62 (*m*, 1 H); 2.11 (*m*, I H); 2.20 (*m*, 2 H); 2.40 (*m*, 1 H), 2.58 (*m*, 1 H); 5.14 (*m*, 1 H); 5.18 (*m*, 1 H); 5.90 (*m*, 1 H); 6.23 (*m*, 2 H). – MS.: 164 (2.5, $C_{11}H_{16}O^+$), 123 (16), 95 (21), 81 (9), 80 (100), 79 (33).

Data of **11**. B.p. 130–140° (bath)/0.05 Torr. – TLC.: Rf 0.33. – GC.: 3.2. – IR.: 3460 (br.), 3050, 2875, 1642, 1378, 1060, 1030, 1000, 917, 710. – ^{1}H-NMR.: 1.20 (*m*, 2 H); 1.39 (*m*, 2 H); 1.69 (*s*, 1 H, D_2O addition removes this signal); 2.37 (*m*, 2 H); 2.59 (*m*, 2 H); 5.14 (*m*, 2 H); 5.96 (*m*, 1 H): 6.34 (*m*, 2 H). – MS.: 164 (0.8, $C_{11}H_{16}O^+$), 123 (11), 95 (18), 81 (8), 80 (100), 79 (29).

3.6. *Preparation of (1*RS,*2*RS,*4*RS*)- and (1*RS,*2*SR,*4*RS*)-2-(2'-methylallyl)bicyclo[2.2.2]oct-5-en-2-ol* (**12** *and* **13**, (5:1)-mixture). Yield 72%.

Data of **12**. B.p. 130–140° (bath)/0.05 Torr. – TLC.: Rf 0.37. – GC.: 3.6. – IR.: 3460 (br.) 3075, 3050, 2860, 1640, 1370, 996, 900, 816, 710. – ^{1}H-NMR.: 0.84–2.26 (*m*, 6 H); 1.79 (*s*, 1 H, D_2O addition removes this signal); 1.84 (br. *s*, 3 H); 2.13 (br. *s*, 2 H); 2.46 (*m*, 2 H); 4.77 (*m*, 1 H); 4.90 (*m*, 1 H); 6.20 (*m*, 2 H). – ^{13}C-NMR.: 142.9*s*, 133.7*d*, 133.4*d*, 114.9*t*, 75.2*s*, 50.9*t*, 42.2*t*, 41.2*d*, 31.2*d*, 25.1*qa*, 24.5*t*, 19.8*t*. – MS.: 178 (0.8, $C_{12}H_{18}O^+$), 123 (14), 95 (22), 81 (7), 80 (100), 79 (24).

Data of **13**. B.p. 130–140° (bath)/0.05 Torr. – TLC.: Rf 0.31. – GC.: 3.6. – IR. (in $CDCl_3$): 3580, 3050, 2880, 1410, 1360, 860. – ^{1}H-NMR.: 0.80–2.30 (*m*, 6 H); 1.70 (*s*, 1 H, D_2O addition removes this signal); 1.86 (br. *s*, 3 H); 2.35 (*m*, 2 H); 2.58 (*m*, 2 H); 4.78 (*m*, 1 H); 4.89 (*m*, 1 H); 6.22 (*m*, 2 H). – MS.: 178 (0.3, $C_{12}H_{18}O^+$), 122 (14), 95 (8), 80 (100), 79 (46), 65 (1).

3.7. *Preparation of (1*RS,*2*RS,*4*RS*)- and (1*RS,*2*SR,*4*RS*)-2-benzylbicyclo[2.2.2]oct-5-en-2-ol* (**14** *and* **15**, (1.5:1)-mixture). Yield 80%.

Data of **14**. B.p. 160–180° (bath)/0.02 Torr. – TLC.: Rf 0.41. – GC. (250°): 7.0. – IR. (in $CDCl_3$): 3580, 3450 (br.), 2870, 1600, 1500, 1000, 700. – ^{1}H-NMR.: 0.81–2.18 (6 H); 1.42 (*s*, 1 H, D_2O addition removes this signal); 2.26 (*m*, 1 H); 2.57 (*m*, 1 H); 2.68 (*m*, 2 H); 6.30 (*m*, 2 H); 7.25 (*m*, 5 H). – ^{13}C-NMR.: 137.3*s*, 133.9*d*, 133.3*d*, 130.5*d*, 128.3*d*, 126.5*d*, 75.5*s*, 49.1*t*, 42.2*t*, 40.0*d*, 31.1*d*, 24.6*t*, 19.5*t*. – MS.: 214 (1.5, $C_{15}H_{18}O^+$), 135 (10), 123 (9), 112 (77), 80 (100), 69 (55).

Data of **15**. B.p. 160–180° (bath)/0.02 Torr. – TLC.: Rf 0.39. – GC. (250°): 7.5. – IR. (in $CDCl_3$): 3580, 3460 (br.), 3050, 2870, 1500, 1458, 1000, 864, 698. – ^{1}H-NMR.: 1.07–2.10 (6 H); 1.61 (*s*, 1 H, D_2O addition removes this signal); 2.35–2.77 (2 H); 2.90 (*m*, 2 H); 6.26 (*m*, 2 H); 7.26 (*m*, 5 H). – ^{13}C-NMR.: 137.9*s*, 135.9*d*, 132.2*d*, 130.5*d*, 128.0*d*, 126.3*d*, 75.6*s*, 45.6*t*, 45.6*t*, 39.9*d*, 30.9*d*, 24.2*t*, 21.2*t*. – MS.: 214 (0, $C_{15}H_{18}O^+$), 122 (15), 91 (3), 80 (100), 79 (55), 65 (1.5), 51 (2.5).

3.8. *Preparation of (1*RS,*2*SR,*4*RS*)- and (1*RS,*2*RS,*4*RS*)-2-phenylbicyclo[2.2.2]oct-5-en-2-ol* (**16** *and* **17**, (1:1)-mixture. Yield 92%.

Data of **16**. M.p. 56–58°; b.p. 160–180° (bath)/0.02 Torr. – TLC.: Rf 0.41. – GC. (250°): 7.6. – IR. (in $CDCl_3$): 3600, 3450 (br.), 3050, 2870, 1496, 1450, 994, 699. – ^{1}H-NMR.: 1.24 (*m*, 2 H); 1.66–2.44 (4 H); 1.93 (*s*, 1 H, D_2O addition removes this signal); 2.70 (*m*, 2 H); 6.18 (*m*, 2 H); 7.26 (*m*, 5 H). – ^{13}C-NMR.: 150.0*s*, 134.0*d*, 133.4*d*, 127.8*d*, 126.5*d*, 126.3*d*, 76.7*s*, 44.5*t*, 42.7*d*, 31.3*d*, 24.3*t*, 20.6*t*. – MS.: 200 (2, $C_{14}H_{16}O^+$), 154 (16), 121 (57), 120 (29), 105 (19), 80 (100), 79 (29).

Data of **17**. B.p. 160–180° (bath)/0.02 Torr. – TLC.: Rf 0.39. – GC. (250°): 7.7. – IR. (in $CDCl_3$): 3430 (br.), 3050, 2870, 1100, 977, 870, 760. – ^{1}H-NMR.: 0.90–1.90 (5 H); 2.15 (*s*, 1 H, D_2O addition removes this signal); 2.35 and 2.51 (*m*, 1 H); 2.77 (*m*, 2 H); 6.44 (*m*, 2 H); 7.40 (*m*, 5 H). – ^{13}C-NMR.: 145.2*s*, 136.7*d*, 132.1*d*, 128.0*d*, 126.9*d*, 126.2*d*, 77.4*s*, 43.8*t*, 43.8*d*, 31.2*d*, 24.3*t*, 20.4*t*. – MS.: 200 (0.5, $C_{14}H_{16}O^+$), 154 (2), 122 (12), 105 (2), 80 (100), 79 (49).

4. Thermolysis of the potassium alkoxides of 2–17 in HMPA. Formation of ketones 18–28 *(cf. Table).* The preparation and thermal fragmentation of the potassium tertiary alkoxides of the epimerically pure (> 95%) bicyclic alcohols **2**, **3**, **6**, **7**, **10**, **11**, **12**, **13**, **14**, **15**, **16** and **17** and the (3:1)-epimeric mixtures of **4**, **5** and **8**, **9** (*cf.* experiments 1–14) were performed using the following standard experimental procedure. A solution of the alcohol (10 mmol for experiments 1, 3, 4, 6, 7, 9 and 11; 1 mmol for experiments 2, 5, 8, 10, 12, 13 and 14) in HMPA (0.5 ml/mmol) was added dropwise, during 10 min, to a stirred slurry of potassium hydride (*Alfa:* 24.1% in mineral oil; 1.1 mol-equiv.) in HMPA (2 ml/mmol) at 10° under N_2. After 30 min the mixture was heated under the conditions described, cooled and then poured into an excess of cold sat. aq. NH_4Cl-solution. Isolation of the reaction products was effected by extraction (ether), work-up (removal of ether at 760 Torr), column chromatography (CH_2Cl_2) and distillation *i.v.*

4.1. *Preparation of 1-(3'-cyclohexenyl)-2-propanone* (**18**). Yield 68% from **2**, 52% from **3**, b.p. 100–110° (bath)/0.1 Torr (lit. [10]: 74–76°/9 Torr). – TLC.: Rf 0.54. – GC.: 2.20. – IR.: 3030, 1710, 1360, 1160, 915, 730, 654. – ^{1}H-NMR.: 1.27 (*m*, 1 H); 1.70 (*m*, 3 H); 2.08 (*m*, 3 H); 2.15 (*s*, 3 H); 2.39 (*d*, $J = 7$, 2 H); 5.65 (*m*, 2 H). – ^{13}C-NMR.: 208.4*s*, 126.9*d*, 126.0*d*, 50.4*t*, 31.6*t*, 30.4*qa*, 29.8*d*, 28.7*t*, 24.8*t*. – MS.: 138 (1.6, $C_9H_{14}O^+$), 95 (3), 81 (13), 80 (100), 79 (36), 67 (3), 59 (6).

4.2. *Preparation of 1-(3'-cyclohexenyl)-2-butanone* (**19**). Yield 70% from **4**/**5** (3:1); b.p. 100–120° (bath)/0.1 Torr (lit. [10]: 135–138°/8 Torr). – TLC.: Rf 0.68. – GC.: 2.60. – IR.: 3030, 1710, 1420, 1380, 1200, 1120, 660. – ^{1}H-NMR.: 1.05 (*t*, $J = 7$, 3 H); 1.27 (*m*, 1 H); 1.30–2.33 (6 H); 2.39 (*d*, $J = 7$, 2 H); 2.42 (*qa*, $J = 7$, 2 H); 5.64 (*m*, 2 H). – ^{13}C-NMR.: 210.7*s*, 126.9*d*, 125.9*d*, 49.1*t*, 36.6*t*, 31.6*t*, 29.8*d*, 28.7*t*, 24.8*t*, 7.8*qa*. – MS.: 152 (4, $C_{10}H_{16}O^+$), 123 (9), 95 (9), 81 (24), 80 (100), 79 (26), 73 (9), 57 (34).

4.3. *Preparation of 1-(3'-cyclohexenyl)-2-pentanone* (**20**). Yield 67% from **6**, 51% from 7; b.p. 120–130° (bath)/0.1 Torr (lit. [10]: 113–115°/20 Torr). – TLC.: Rf 0.70. – GC.: 3.1 – IR.: 3030, 1710, 1440, 1200, 1125, 660. – ^{1}H-NMR.: 0.92 (*t*, *J* = 7, 3 H); 1.27 (*m*, 1 H); 1.62 (*m*, 2 H); 1.70 (*m*, 2 H); 2.06 (*m*, 2 H); 2.14 (*m*, 2 H); 2.38 (*d*, *J* = 7, 2 H); 2.39 (*t*, *J* = 7, 2 H); 5.65 (*m*, 2 H). – MS.: 166 (3, $C_{11}H_{18}O^+$), 123 (2), 95 (4), 87 (12), 81 (12), 80 (100), 79 (18), 71 (9).

4.4. *Preparation of 1-(3'-cyclohexenyl)-3-methyl-2-butanone* (**21**). Yield 64% from **8**/**9** (3:1), b.p. 100–120° (bath)/0.1 Torr (lit. [10]: 96–99°/12 Torr). – TLC.: Rf 0.71. – GC.: 2.6. – IR.: 3030, 1710, 1470, 1384, 1200, 1030, 660. – ^{1}H-NMR.: 1.05 and 1.13 (2*s*, 6 H); 1.00–2.24 (7 H); 2.42 (*d*, *J* = 7, 2 H); 2.59 (*m*, 1 H); 5.64 (*m*, 2 H). – MS.: 166 (9, $C_{11}H_{18}O^+$), 123 (20), 95 (19), 87 (18), 81 (35), 80 (100), 79 (34), 71 (100).

4.5. *Preparation of 1-(3'-cyclohexenyl)-4-penten-2-one* (**22**) *and (*E*)-1-(3-cyclohexenyl)-3-penten-2-one* (**23**) ((4:1)-mixture). Yield 74% from **10**.

Data of **22**. B.p. 120–130° (bath)/0.1 Torr. – TLC.: Rf 0.75. – GC.: 3.6. – IR.: 3080, 3025, 1710, 1640, 996, 920, 660. – ^{1}H-NMR.: 1.26 (*m*, 1 H); 1.68 (*m*, 2 H); 2.10 (*m*, 4 H); 2.41 (*d*, *J* = 7, 2 H); 3.18 (br. *d*, *J* = 7, 2 H); 5.17 (2 H); 5.65 (*m*, 2 H); 5.93 (*m*, 1 H). – ^{13}C-NMR.: 208.1*s*, 130.8*d*, 126.9*d*, 126.0*d*, 118.7*t*, 48.9*t*, 48.4*t*, 31.6*t*, 29.5*d*, 28.6*t*, 24.8*t*. – MS.: 164 (8, $C_{11}H_{16}O^+$), 123 (38), 95 (50), 81 (42), 80 (100), 79 (94), 67 (23).

Data of **23**. B.p. 120–130° (bath)/0.1 Torr. – TLC.: Rf 0.59. – GC.: 4.7. – IR. (in $CDCl_3$): 3030, 1670, 1630, 1440, 1294, 978. – ^{1}H-NMR.: 1.28 (*m*, 1 H); 1.71 (*m*, 2 H); 1.90 (*d*, *J* = 7, 3 H); 1.96–2.14 (4 H); 2.48 (*d*, *J* = 7, 2 H); 5.65 (*m*, 2 H); 6.14 (*m*, 1 H); 6.86 (*m*, 1 H). – ^{13}C-NMR.: 199.9*s*, 142.3*d*, 132.4*d*, 126.8*d*, 126.0*d*, 46.6*t*, 31.6*t*, 30.2*d*, 28.7*t*, 24.8*t*, 18.1*qa*. – MS.: 164 (5, $C_{11}H_{16}O^+$), 122 (6), 94 (6), 85 (47), 80 (100), 79 (50), 69 (22).

Thermolysis of the potassium alkoxide of **11** afforded a mixture of **22** and **23** ((4:1)-mixture, yield *ca.* 5–10%), **1** (49%) and phenol (16%). Spectral data of these products were identical with those of authentic samples.

4.6. *Preparation of 1-(3'-cyclohexenyl)-4-methyl-4-penten-2-one* (**24**) *and 1-(3'-cyclohexenyl)-4-methyl-3-penten-2-one* (**25**) ((4:1)-mixture). Yield 76% from **12**.

Data of **24**. B.p. 120–130° (bath)/0.1 Torr. – TLC.: Rf 0.78. – GC.: 3.8. – IR.: 3080, 3025, 1710, 1650, 1440, 1380, 900, 660. – ^{1}H-NMR.: 0.80–2.33 (7 H); 1.75 (*m*, 3 H); 2.42 (*m*, 2 H); 3.10 (br. *s*, 2 H); 4.50 (*m*, 1 H); 4.91 (*m*, 1 H); 5.64 (*m*, 2 H). – MS.: 178 (2.5, $C_{12}H_{18}O^+$), 123 (34), 95 (59), 80 (57), 79 (100), 67 (19).

Data of **25**. B.p. 120–130° (bath)/0.1 Torr. – TLC.: Rf 0.67. – GC.: 4.7. – IR.: 3030, 1685, 1620, 1440, 1380, 1120, 1034, 660. – ^{1}H-NMR.: 0.80–2.10 (7 H); 1.86 (*m*, 3 H); 2.14 (*m*, 3 H); 2.36 (*m*, 2 H); 5.64 (*m*, 2 H); 6.07 (*m*, 1 H). – MS.: 178 (3.6, $C_{12}H_{18}O^+$), 99 (31), 98 (36), 83 (100), 80 (25), 55 (25).

Thermolysis of the potassium alkoxide of **13** afforded a mixture of **24** and **25** ((4:1)-mixture, yield: *ca.* 5–10%), **1** (46%) and phenol (15%). Spectral data of these products were identical with those of authentic samples.

4.7. *Preparation of 1-(3'-cyclohexenyl)-3-phenyl-2-propanone* (**26**). Yield 54% from **14**, b.p. 160–180°/0.05 Torr (lit. [10]: 158–159°/0.6 Torr). – TLC.: Rf 0.77. – GC. (250°): 7.4. – IR. (in $CDCl_3$): 3040, 2850, 1710, 1500, 1458, 1440, 1280, 700. – ^{1}H-NMR.: 1.26 (*m*, 1 H); 1.44–2.33 (6 H); 2.41 (*d*, *J* = 7, 2 H); 3.67 (*s*, 2 H); 5.59 (*m*, 2 H); 7.23 (*m*, 5 H). – MS.: 214 (11, $C_{15}H_{18}O^+$), 135 (23), 123 (32), 95 (61), 91 (42), 81 (39), 80 (72), 79 (100).

Thermolysis of the potassium alkoxide of **15** afforded a mixture of **1** (50%) and phenol (18%). The spectral data of these products were identical with those of authentic samples.

4.8. *Preparation of ω-(3'- and 2'-cyclohexenyl)acetophenone* (**27**/**28**) *and 2-(3'- and 2'-cyclohexenyl)-1-phenylethanol* (**29**/**30**) (diastereoisomeric mixtures) from **16**.

Data of **27**[10], **28**[11]((3:7)-mixture of 3'- and 2'-isomers). Yield 4 mg, 2%, b.p. 150–160° (bath)/0.04 Torr. – TLC.: Rf 0.78. – GC. (250°): 5.4. – IR.: 3060, 3030, 1680, 1600, 1582, 1280, 1004, 756, 693. – ^{1}H-NMR.: 1.22–2.38 (7 H); 2.90–2.96 (2 H); 5.56–5.76 (2 H); 7.46, 7.55 and 7.95 (*m*, 5 H). – MS.: 200 (14, $C_{14}H_{16}O^+$), 157 (3), 144 (4), 121 (42), 105 (100), 80 (61).

Data of **29**/**30** ((3:7)-mixture of 3'- and 2'-isomers). Yield 12 mg, 6%, b.p. 150–160° (bath)/0.04 Torr. – TLC.: Rf 0.50. – IR. (in $CDCl_3$): 3600, 3450 (br.), 3030, 2930, 2850, 1440, 1310. – ^{1}H-NMR.: 1.20–2.20 (10 H); 5.60 (*m*, 2 H); 7.33 (*m*, 5 H). – MS.: 202 (0.5, $C_{14}H_{18}O^+$), 184 (1), 121 (100), 105 (6), 91 (1.5), 77 (7), 43 (74).

Also isolated was a (2:1)-mixture (45%) of 1-phenylethanol and acetophenone whose spectral data were identical to those of authentic samples.

Thermolysis of the potassium alkoxide of **17** afforded a (3:1)-mixture (6%) of **27/28** and **29/30** together with a (2:1)-mixture (48%) of 1-phenylethanol and acetophenone.

5. Treatment of 18 with excess of KH. – A solution of **18** (69 mg, 0.5 mmol) in 0.5 ml of HMPA was added dropwise to a stirred slurry of KH (1 mmol) in 1 ml of HMPA at 10° under N_2. The mixture was heated at 120° for 2 h, cooled and poured into cold sat. aq. NH_4Cl-solution. Extraction (ether), work-up, isolation of the products by column chromatography (CH_2Cl_2) and distillation *i.v.* afforded a (3:1)-mixture[14]) (40 mg) of **18** and 1-(2'-cyclohexenyl)-2-propanone (^{13}C-NMR.: 208.7*s*, 130.5*d*, 127.9*d*, 50.1*t*, 31.3*d*, 30.5*qa*, 29.0*t*, 25.1*t*, 21.1*t*).

6. Decomposition of the potassium enolates of 18 in HMPA (*cf.* footnote 9). A solution of **18** (69 mg, 0.5 mmol) in 0.3 ml of HMPA was added dropwise to a stirred slurry of potassium hydride (0.6 mmol) in 2 ml of HMPA at 25° under N_2. The mixture was stirred at 25° and after 1 h, 2 h, 4 h, 8 h and 24 h an aliquot was added to an excess of trimethylchlorosilane. In each case addition of sat. aq. NH_4Cl-solution, extraction (pentane) and work-up afforded an oil which was analyzed by GC.[15]).

Using the same quantities the experiment was repeated at 120° and aliquots were taken after 1 h and 2 h. Isolation of organic material as described above was followed by GC. analysis of the product mixtures.

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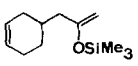
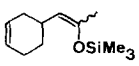
[14]) Analysis effected by GC. (capillary column) and NMR.

[15]) For comparison purposes a mixture (>9:1) of the trimethylsilyl enol ethers of **18**, **i** and **ii**, (b.p. 100–120° (bath)/0.2 Torr. – GC.: 1.3. – IR.: 3030, 1620, 1440, 1250, 1160, 1010, 850, 655. – ^{1}H-NMR.: 0.20 (*s*, 9 H); 0.80–2.20 (9 H); 5.66 (*m*, 2 H). – MS.: 210 (14, $C_{12}H_{22}OSi^+$), 167 (31), 156 (38), 147 (12), 130 (60), 115 (100) was prepared from **18** by kinetic deprotonation (LDA/THF/–78°) followed by treatment with trimethylchlorosilane.



i



ii