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STERICALLY CROWDED CYCLOHEXANES - 7[1]. SYNTHESIS, CRYSTAL STRUCTURE, CONFORMATION AND DYNAMICS OF HEXASPIRO[2.0.3.0.2.0.3.0.3.0.3.0]DOCOSANE AND HEXASPIRO[2.0.3.0.3.0.3.0.3.0.3.0]TRICOSANE

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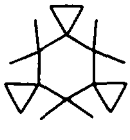
ABSTRACT

The synthesis, crystal structure, conformation and dynamics of hexaspiro[2.0.3.0.2.0.3.0.3.0.3.0]docosane **6** and hexaspiro[2.0.3.0.3.0.3.0.3.0.3.0]tricosane **7** are described. Both compounds adopt a chair conformation in the solid state and in solution. Their barriers of inversion were inaccessible by DNMR but could be determined from equilibration studies with stereoselectively labeled [1-^{13}C]-**6** and [1,1-D$_2$]-**7**. The results were as follows: [1-^{13}C]$_{a,e}$-**6**: $\Delta G^{\neq}_{339}$ = 112.1 kJ/mol and [1,1-D$_2$]$_{a,e}$-**7**: $\Delta G^{\neq}_{423}$ = 136.0 kJ/mol. The stereoisomers of [1-^{13}C]-**6** and [1,1-D$_2$]-**7** thus represent two further examples of conformational isomerism within the cyclohexane family.

1. INTRODUCTION

Based on the finding that hexaspirane **5** adopts a chair conformation in the crystal but prefers a chair-to-twistboat equilibrium in solution[2] we recently suggested that per(cyclo)alkylated cyclohexanes with strongly alternating substituent opening angles, as in **1**, should adopt a pure twistboat conformation whereas those with identical opening angles, as in **4** and **8**, should retain the usual chair conformation. Indeed, pure twistboat conformations have been found for **1**[3,4] and **2**[3], and pure chair conformations for **3**[5] and **4**[5,6].



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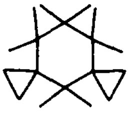

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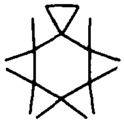

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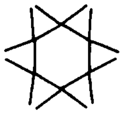

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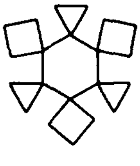

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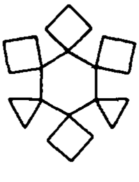

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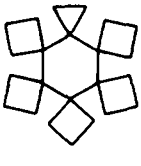

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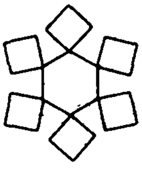

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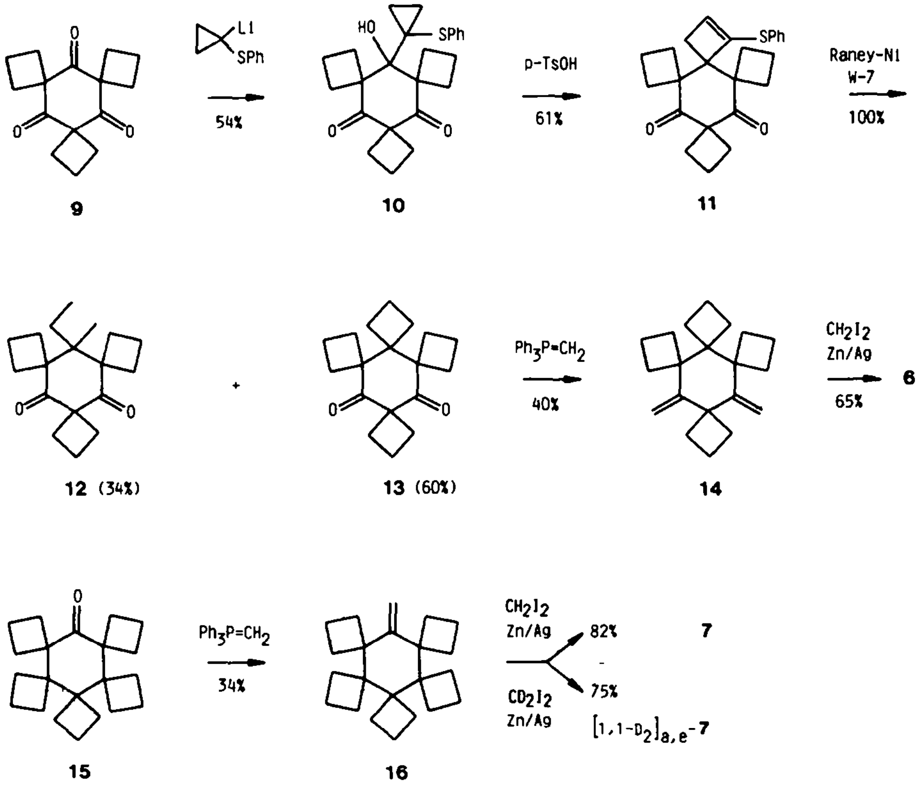
The height of the barriers of inversion is largely governed by the number and degree of alternations, respectively. As the number or degree of alternations decreases, the corresponding barrier of inversion increases. This has been found true for passing from **1** ($\Delta G^{\neq}_{298}$ = 19.7 kJ/mol)[3] over **2** ($\Delta G^{\neq}_{300}$ = 56.9 kJ/mol)[3] and **3** ($\Delta G^{\neq}_{373}$ = 68.2 kJ/mol)[5] to **4** ($\Delta G^{\neq}_{298}$ = 72.4 kJ/mol)[5], and for passing from **1** to **5** ($\Delta G^{\neq}_{298}$ = 92.0 kJ/mol)[2]. A tentative explanation on the basis of nonbonding interactions has been given [3].

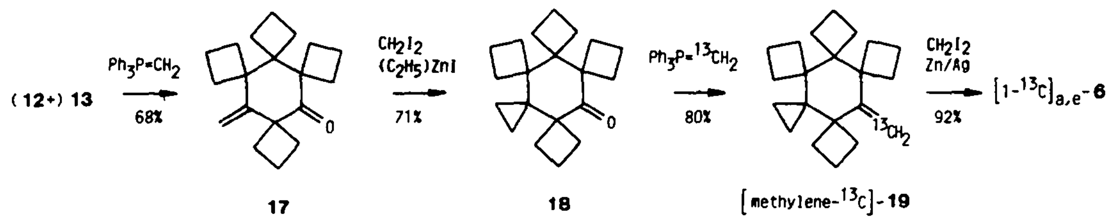
The already extremely high barrier of inversion of **5** and the distinct increase in the barriers of inversion from **1** to **4** rendered the hitherto unknown hexaspiranes **6**, **7** and **8** to promising candidates for a possible observation of conformational isomerism[7], provided that stereoselectively labeled derivatives would be available. We herein report on the synthesis and structure of **6** and **7**, and on our finding that their barriers of inversion are indeed so high that they could only be determined from equilibration studies with stereoselectively labeled [1-^{13}C]-**6** and [1,1-D_2]-**7**. Some consequences for the structure and dynamics of the still unknown **8** are discussed.

2. SYNTHESES

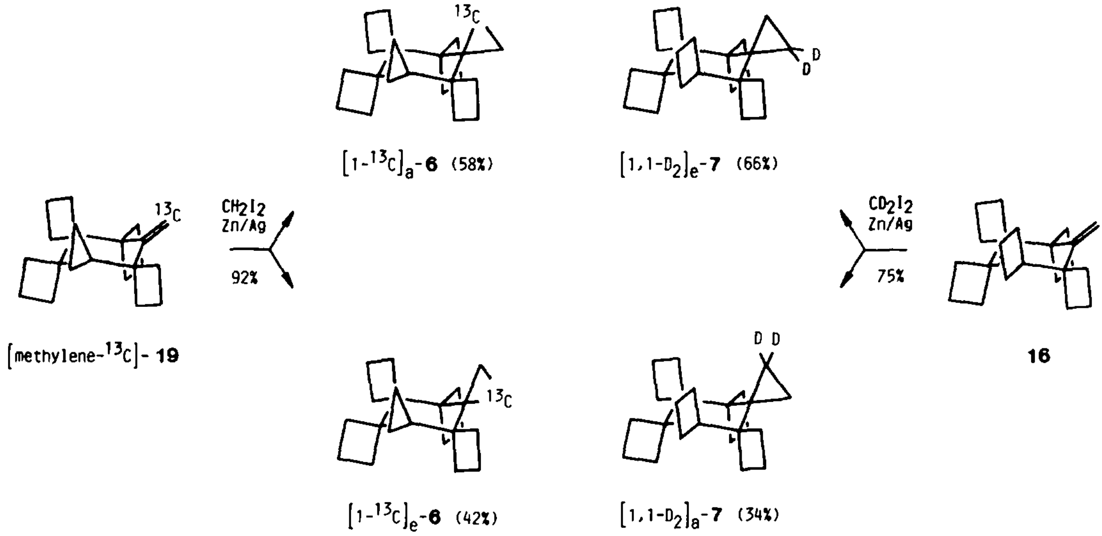
The syntheses of **6** and **7** are based on ketones **9**[8] and **15**[9], respectively. According to a general procedure for the spiroannulation of cyclobutanes developed by Trost[10], trione **9** was treated with 1-lithiocyclopropyl phenyl sulphide to yield the β-hydroxysulphide **10**, which was then rearranged to thioenol ether **11** by treatment with p-toluenesulphonic acid in benzene. Reduction was accomplished with Raney nickel W-7[11] yielding a 1:2 mixture of diones **12** and **13**, which could be separated by gas chromatography but was treated with methylene triphenylphosphorane as such. Dimethylenation of dione **13** could be achieved selectively and subsequent cyclopropanation of the resulting diene **14** yielded the desired **6**. For the synthesis of **7** ketone **15**[9] was first methylenated to **16** and subsequently cyclopropanated to **7**. As will be shown later this sequence could also be used for a stereoselective synthesis of [1,1-D_2]-**7**.



According to their ^{13}C-NMR spectra (20.2 MHz, $CDCl_3$[12], 25°C) both **6** (δ = 1.44, 5.97, 16.12, 16.28, 16.59, 23.78, 24,16, 24.96, 25.66, 26.60, 28.44, 33.36, 47.15, 48.21, 51.84) and **7** (δ = -0.01, 6.89, 16.44, 16.52, 16.57, 21.36, 25.10, 25.43, 25.80, 27.46, 28.49, 28.93, 48.34, 49.58, 50.80) exist at room temperature in a fixed chair conformation. As the ^{1}H-NMR spectra remained unchanged up to +180°C, inversion barriers distinctly above 100 kJ/mol could be expected and the necessity of equilibration studies with stereoselectively labeled derivatives became obvious. Syntheses of $[1\text{-}^{13}C]_{a,e}$-**6** and $[1,1\text{-}D_2]_{a,e}$-**7** were therefore envisaged.

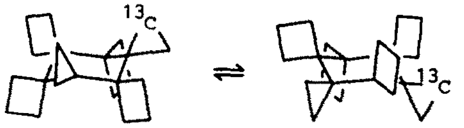


$[1\text{-}^{13}C]_{a,e}$-**6** was obtained as follows: selective monomethylenation of dione **13** yielded enone **17**, which was first cyclopropanated to ketone **18**[13] and subsequently methylenated to [methylene-^{13}C]-**19**. When this material was cyclopropanated to $[1\text{-}^{13}C]_{a,e}$-**6** and then subjected to a ^{13}C-NMR analysis (50.3 MHz, $CDCl_3$[12]), two lines at δ = 1.44 and 5.97 (cyclopropane-$\underline{C}H_2$) with an intensity ratio of 58:42 indicated that one stereoisomer had formed in significant excess. For the remaining synthesis of $[1,1\text{-}D_2]_{a,e}$-**7**, olefin **16** was methylenated with diiodomethane-d_2. This time we inspected the ^{1}H-NMR spectrum (200 MHz, $CDCl_3$, $CHCl_3$ int.[12]) and found two lines at δ = 0.44 and 0.56 (cyclopropane-$C\underline{H}_2$) with an intensity ratio of 66:34, which corresponded to two lines at δ = 6.65 and -0.24 (cyclopropane-$\underline{C}H_2$) in the ^{13}C-NMR spectrum (50.3 MHz, $CDCl_3$[12]), as evidenced by a ^{13}C-^{1}H-correlation[14] of an equilibrated sample. Albeit we believe that both [methylene-^{13}C]-**19** and **16** were cyclopropanated stereoselectively by an equatorial attack of the reagent leading to $[1\text{-}^{13}C]_a$-**6** and $[1,1\text{-}D_2]_e$-**7** in excess, this stereochemical assignment remains to be proved[15]. Nevertheless, whatever the result will be, the stereochemical outcome of both cyclopropanations had been preserved by sufficiently high barriers of inversion.

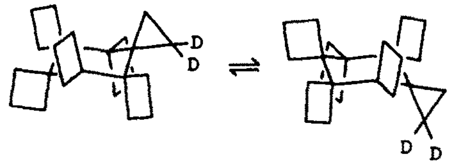


3. DYNAMICS

Preliminary measurements revealed that the equilibration of the stereoisomers of $[1\text{-}^{13}C]$-**6** and $[1,1\text{-}D_2]$-**7** could most conveniently be followed by ^{13}C-NMR spectroscopy (50.3 MHz, nitrobenzene-d_5[12]) at +66 °C and ^{1}H-NMR spectroscopy (200 MHz, nitrobenzene-d_5[12]) at +150 °C, respectively. The spectra were taken at appropriate times and the decrease in concentration of $[1\text{-}^{13}C]_a$-**6**[16] and $[1,1\text{-}D_2]_e$-**7**[16] measured by careful integration of the corresponding resonance lines of the cyclopropane ring (Fig. 1). As could be expected, the equilibrations followed first order kinetics[17] (Fig. 2) and led to k($[1\text{-}^{13}C]_a$-**6**) = k($[1\text{-}^{13}C]_e$-**6**) = $(3.749 \pm 0.083)\cdot 10^{-5}$ sec^{-1} at +66.0 ± 0.5 °C and k($[1,1\text{-}D_2]_e$-**7**) = k($[1,1\text{-}D_2]_a$-**7**) = $(1.435 \pm 0.034)\cdot 10^{-4}$ sec^{-1} at +150.0 ± 0.5 °C[18]. Insertion of these data into the Eyring equation yielded the free energies of activation as $\Delta G^{\ddagger}_{339}$ = 112.1 ± 0.2 kJ/mol ($[1\text{-}^{13}C]_{a,e}$-**6**) and $\Delta G^{\ddagger}_{423}$ = 136.0 ± 0.2 kJ/mol ($[1,1\text{-}D_2]_{a,e}$-**7**), and thereby two of the highest barriers of inversion ever detected for a cyclohexane[19].



$[1\text{-}^{13}C]_{a,e}$-**6**



$[1,1\text{-}D_2]_{a,e}$-**7**

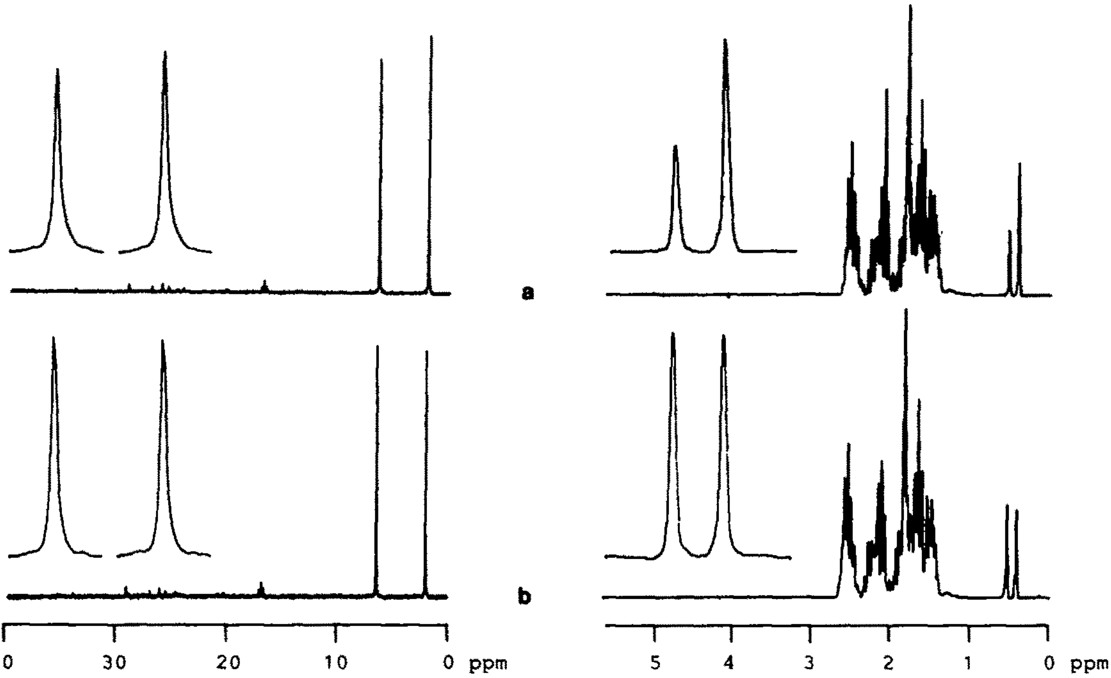


Fig. 1. ^{13}C-NMR spectra (50.3 MHz, nitrobenzene-d_5[12], +66.0°C) of $[1\text{-}^{13}C]_{a,e}$-**6** and ^1H-NMR spectra (200 MHz, nitrobenzene-d_5[12], +150.0°C) of $[1,1\text{-}D_2]_{a,e}$-**7**: (a) before and (b) after equilibration. Spectral parameters and details concerning the kinetic analysis are given in the experimental part.

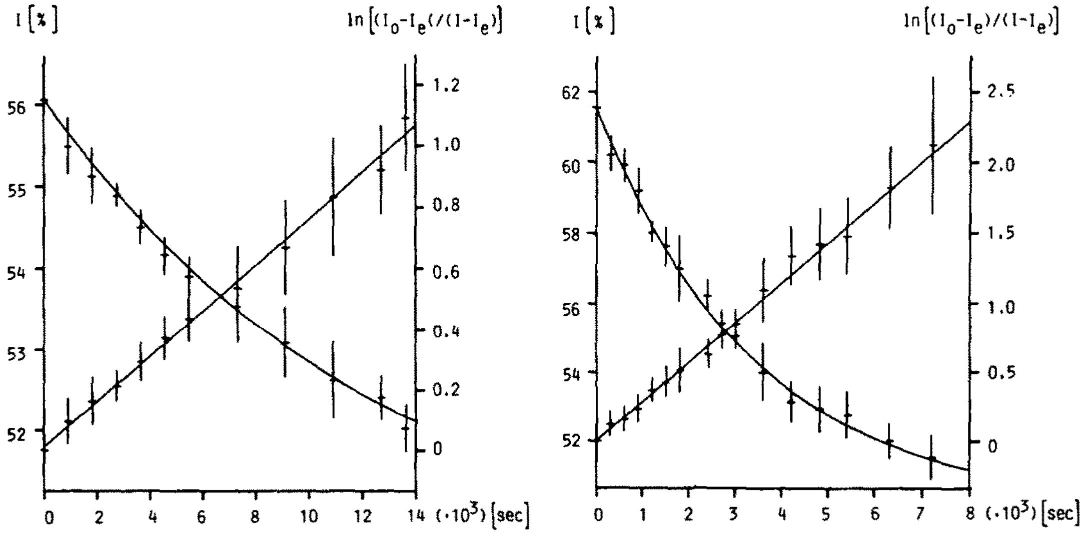


Fig. 2. Time course of the decrease in concentration of $[1\text{-}^{13}C]_a$-**6** at +66.0°C (left) and $[1,1\text{-}D_2]_e$-**7** at +150.0°C (right), and least-squares approximation of $\ln[(I_o-I_e)/(I-I_e)] = [k([1\text{-}^{13}C]_a\text{-}\mathbf{6}) + k([1\text{-}^{13}C]_e\text{-}\mathbf{6})]\cdot t$ (left) and $\ln[(I_o-I_e)/(I-I_e)] = [k([1,1\text{-}D_2]_e\text{-}\mathbf{7}) + k([1,1\text{-}D_2]_a\text{-}\mathbf{7})]\cdot t$ (right). I_o, I and I_e refer to the initial, actual, and equilibrium concentrations of $[1\text{-}^{13}C]_a$-**6** and $[1,1\text{-}D_2]_e$-**7**, respectively.

4. CRYSTAL STRUCTURES

In view of a future reparametrization of empirical force fields, especially of the terms describing nonbonding interactions[20], we determined the crystal structures of both **6** and **7**. In the solid state, **6** exhibits exact mirror symmetry with two opposite substituent rings in the mirror plane, while **7** lies twofold disordered on a centre of symmetry (Fig.3). In both compounds the central ring adopts a chair conformation with bond lengths (Tables 1,4), bond angles (Tables 2,5) and torsion angles (Tables 3,6) similar to those observed for **5**[2]. As in **5**, striking differences between the bond lengths within the four-membered rings are observed: those to the spiro atoms (average of the opening angles: 85.3°) are considerably elongated (average: 1.58 Å), those to the peripheral carbon atoms shortened (average: 1.51 Å). Differences in bond lengths as large as 0.18 Å occur within the same ring, which illustrates the extremely strong nonbonding interactions apparently present in both molecules. Accordingly, the nonbonded distances of carbon atoms in 1,2-e,e or 1,2-e,a positions are rather short (average: 3.1 Å) and the same is true for carbon atoms in 1,3-a,a position (average: 3.4 Å). As would have been expected, all cyclobutane rings are planar or only slightly puckered (torsion angles: 0-4°). A discussion of the consequences of the observed structural anomalies for the ground state energies of **6** and **7** as compared to **5** must await a detailed force-field study, which is in progress.

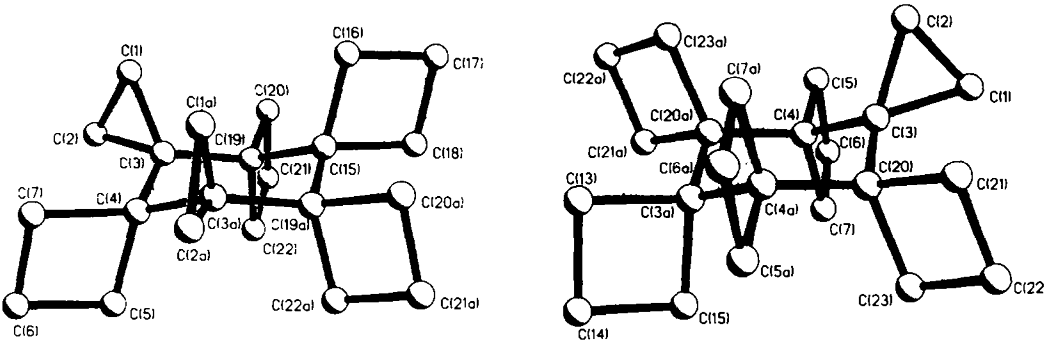


Fig.3. Perspective views of the carbon skeletons of **6** (left) and **7** (right) with the crystallographic atom numbering

C(1)-C(2)	1.484(4)	C(4)-C(5)	1.536(4)	C(15)-C(18)	1.627(4)	C(19)-C(20)	1.602(3)
C(1)-C(3)	1.432(3)	C(4)-C(7)	1.635(4)	C(15)-C(19)	1.574(3)	C(19)-C(22)	1.491(3)
C(2)-C(3)	1.530(3)	C(5)-C(6)	1.527(5)	C(16)-C(17)	1.581(6)	C(20)-C(21)	1.452(4)
C(3)-C(4)	1.558(3)	C(6)-C(7)	1.450(5)	C(17)-C(18)	1.483(5)	C(21)-C(22)	1.552(4)
C(3)-C(19)	1.574(3)	C(15)-C(16)	1.529(4)				

Table 1. Bond lengths (Å) for **6** with estimated standard deviations in parentheses

C(2)-C(1)-C(3)	63.3(2)	C(5)-C(4)-C(7)	78.6(2)	C(15)-C(18)-C(17)	98.1(3)
C(1)-C(2)-C(3)	56.7(2)	C(4)-C(5)-C(6)	98.8(3)	C(3)-C(19)-C(15)	113.2(2)
C(1)-C(3)-C(2)	60.0(2)	C(5)-C(6)-C(7)	84.9(3)	C(3)-C(19)-C(20)	118.5(2)
C(1)-C(3)-C(4)	117.9(2)	C(4)-C(7)-C(6)	97.7(3)	C(3)-C(19)-C(22)	108.7(2)
C(2)-C(3)-C(4)	115.1(2)	C(16)-C(15)-C(18)	80.4(2)	C(15)-C(19)-C(20)	109.4(2)
C(1)-C(3)-C(19)	113.3(2)	C(16)-C(15)-C(19)	114.6(1)	C(15)-C(19)-C(22)	117.1(2)
C(2)-C(3)-C(19)	119.1(2)	C(18)-C(15)-C(19)	117.4(1)	C(20)-C(19)-C(22)	87.9(2)
C(4)-C(3)-C(19)	118.3(2)	C(19)-C(15)-C(19a)	109.7(2)	C(19)-C(20)-C(21)	90.2(2)
C(3)-C(4)-C(3a)	104.7(2)	C(15)-C(16)-C(17)	98.2(3)	C(20)-C(21)-C(22)	91.2(2)
C(3)-C(4)-C(5)	117.5(1)	C(16)-C(17)-C(18)	83.4(3)	C(19)-C(22)-C(21)	90.7(2)
C(3)-C(4)-C(7)	118.9(1)				

Table 2. Bond angles (°) for **6** with estimated standard deviations in parentheses

C(3a)-C(4)-C(3)-C(19)	50.6(3)	C(7)-C(4)-C(3)-C(1)	43.8(3)	C(2)-C(3)-C(19)-C(22)	-69.8(2)
C(4)-C(3)-C(19)-C(15)	-53.4(2)	C(7)-C(4)-C(3)-C(2)	-24.1(3)	C(16)-C(15)-C(19)-C(20)	51.5(3)
C(19a)-C(15)-C(19)-C(3)	47.6(3)	C(1)-C(3)-C(19)-C(20)	-39.2(3)	C(18)-C(15)-C(19)-C(20)	-40.3(3)
C(19)-C(20)-C(21)-C(22)	-1.2(2)	C(2)-C(3)-C(19)-C(20)	28.3(3)	C(18)-C(15)-C(19)-C(22)	57.5(3)
C(5)-C(4)-C(3)-C(2)	67.8(3)				

Table 3. Selected torsion angles (°) for **6** with estimated standard deviations in parentheses

C(1)-C(2)	1.533(15)	C(3a)-C(15)	1.619(10)	C(5)-C(6)	1.484(3)	C(20)-C(21)	1.569(3)
C(1)-C(3)	1.534(12)	C(3)-C(20)	1.538(3)	C(6)-C(7)	1.499(3)	C(20)-C(23)	1.563(3)
C(2)-C(3)	1.494(12)	C(4)-C(5)	1.573(3)	C(13)-C(14)	1.605(12)	C(21)-C(22)	1.479(4)
C(3)-C(4)	1.542(3)	C(4)-C(7)	1.567(3)	C(14)-C(15)	1.580(15)	C(22)-C(23)	1.502(4)
C(3a)-C(13)	1.607(8)	C(4a)-C(20)	1.531(3)				

Table 4. Bond lengths (Å) for **7** with estimated standard deviations in parentheses

C(3)-C(1)-C(2)	58.3(6)	C(20a)-C(3a)-C(15)	114.3(6)	C(15)-C(14)-C(13)	92.1(5)
C(3)-C(2)-C(1)	60.9(7)	C(5)-C(4)-C(3)	114.1(2)	C(14)-C(15)-C(3a)	88.7(8)
C(2)-C(3)-C(1)	60.8(7)	C(5)-C(4)-C(20a)	113.5(2)	C(4a)-C(20)-C(3)	112.1(2)
C(4)-C(3)-C(1)	119.7(6)	C(7)-C(4)-C(3)	114.7(2)	C(4a)-C(20)-C(21)	114.1(2)
C(4)-C(3)-C(2)	118.0(7)	C(7)-C(4)-C(5)	85.3(2)	C(4a)-C(20)-C(23)	115.1(2)
C(20)-C(3)-C(1)	119.1(6)	C(7)-C(4)-C(20a)	114.4(2)	C(21)-C(20)-C(3)	113.9(2)
C(20)-C(3)-C(2)	117.5(7)	C(20a)-C(4)-C(3)	112.3(2)	C(23)-C(20)-C(3)	114.0(2)
C(20)-C(3)-C(4)	112.6(2)	C(6)-C(5)-C(4)	91.9(2)	C(23)-C(20)-C(21)	85.2(2)
C(13)-C(3a)-C(4a)	112.1(5)	C(7)-C(6)-C(5)	91.0(2)	C(22)-C(21)-C(20)	92.4(2)
C(15)-C(3a)-C(4a)	112.4(6)	C(6)-C(7)-C(4)	91.6(2)	C(23)-C(22)-C(21)	90.7(2)
C(15)-C(3a)-C(13)	90.6(5)	C(14)-C(13)-C(3a)	88.3(6)	C(22)-C(23)-C(20)	91.8(2)
C(20a)-C(3a)-C(13)	113.1(5)				

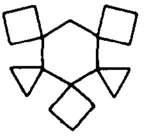
Table 5. Bond angles (°) for **7** with estimated standard deviations in parentheses

C(20a)-C(4)-C(3)-C(20)	52.3(2)	C(5)-C(4)-C(3)-C(2)	41.4(7)	C(7)-C(4)-C(20a)-C(21a)	-50.4(2)
C(4)-C(3)-C(20)-C(4a)	-52.2(2)	C(7)-C(4)-C(3)-C(1)	67.0(6)	C(23a)-C(20a)-C(3a)-C(13)	47.5(5)
C(3)-C(20)-C(4a)-C(3a)	52.0(2)	C(1)-C(3)-C(20)-C(21)	28.6(6)	C(21a)-C(20a)-C(3a)-C(13)	-48.0(5)
C(7)-C(6)-C(5)-C(4)	-3.5(2)	C(1)-C(3)-C(20)-C(23)	-66.9(6)	C(21a)-C(20a)-C(3a)-C(15)	53.8(6)
C(15)-C(14)-C(13)-C(3a)	-3.3(6)	C(2)-C(3)-C(20)-C(21)	-41.5(7)	C(13)-C(3a)-C(4a)-C(5a)	47.8(5)
C(23)-C(22)-C(21)-C(20)	-1.2(2)	C(5)-C(4)-C(20a)-C(23a)	-50.9(2)	C(13)-C(3a)-C(4a)-C(7a)	-48.3(5)
C(5)-C(4)-C(3)-C(1)	-29.2(6)	C(5)-C(4)-C(20a)-C(21a)	45.3(2)	C(15)-C(3a)-C(4a)-C(5a)	-52.5(6)

Table 6. Selected torsion angles (°) for **7** with estimated standard deviations in parentheses

5. DISCUSSION

Obviously, the large increase in the barriers of inversion in passing from **5** (ΔG^{*}_{298} = 92.0 kJ/mol)$^{2)}$ over $[1\text{-}^{13}C]_{a,e}$-**6** (ΔG^{*}_{339} = 112.1 kJ/mol) to $[1,1\text{-}D_2]_{a,e}$-**7** (ΔG^{*}_{423} = 136.0 kJ/mol) is caused by a corresponding decrease in the number of alternations from three (**5**) over two ($[1\text{-}^{13}C]_{a,e}$-**6**) to one ($[1,1\text{-}D_2]_{a,e}$-**7**). We therefore expect that the still unknown hexaspirane **8**, which shows no alternations at all, will exhibit the highest barrier of inversion of all cyclohexanes known so far. We suppose that the large increase in the barriers of inversion within the series **5**, $[1\text{-}^{13}C]_{a,e}$-**6** and $[1,1\text{-}D_2]_{a,e}$-**7** is at least partly due to a corresponding increase in the number of energetically unfavourable 1,2-synperiplanar interactions in the half-chair transition state of the chair-to-chair interconversion. To what extent the ground-state energies are involved will be clarified by a comparative force-field study, which is in progress.



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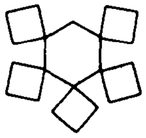

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The barrier of inversion of the still unknown hexaspirane **8** can be estimated from a comparative study of the hexaspiranes **5**, **6** and **7**, and the pentaspiranes **20** and **21**. Out of these, **20** is related to both **5** and **6**, and **21** to both **7** and **8**. Their synthesis, structure, conformation and dynamics are reported in a separate paper of this issue.

6. EXPERIMENTAL

IR spectra were recorded on a Perkin-Elmer 225 or 298 spectrophotometer. ^{1}H- and ^{13}C-NMR spectra were measured on Varian FT 80A, XL100 or XL200 spectrometers. Mass spectra were obtained with a Varian MAT 731 operated at 70 eV. Analytical and preparative gas chromatography was carried out on a

Varian 920, Intersmat IGC 16 or Carlo-Erba FTV 2450 instrument employing a thermal conductivity detector and hydrogen as carrier gas. Product ratios were not corrected for relative response. R_f values are quoted for Machery & Nagel Polygram SIL G/UV$_{254}$ plates. Colourless substances were detected by oxidation with 3.5% alcoholic 12-molybdophosphoric acid (Merck) and subsequent warming. Melting points are not corrected.

15-Hydroxy-15-(1'-phenylthiocycloprop-1'-yl)trispiro[3.1.3.1.3.1]pentadecane-5,10-dione 10: To a stirred solution of 9.5 g (63 mmol) cyclopropyl phenyl sulphide[10] in 200 ml of tetrahydrofuran at 0°C were added 40 ml (64 mmol) of a 1.6 molar solution of n-butyllithium in hexane. After 2h at 0°C a solution of 5.20 g (21 mmol) **9**[8] in 2 ml of tetrahydrofuran was added, and after additional 2h at 0°C and 2.5h at r.t. the reaction was complete according to tlc analysis [CH_2Cl_2; R_f = 0.25 (**10**) and 0.39 (**9**)]. Water (5 ml) was added, the mixture concentrated on a rotary evaporator (bath temperature 70°C/15 torr), the residue dissolved in dichloromethane (200 ml), washed with water (3 x 30 ml) and concentrated again (bath temperature 70°C/15 torr). Crystallization from pentane yielded a first crop of 3.45 g (41%) **10** (mp 126-128°C), chromatography of the mother liquor on silica gel (0.05-0.20 mm) in hexane (column 30 x 1.5 cm) gave first recovered cyclopropyl phenyl sulphide and then, using hexane/ether (1:1) as eluent, a second crop of 1.05 g (13%) **10** as slowly crystallizing oil. Recrystallization from pentane/ether yielded analytically pure **10** as colourless crystals (mp 131-132°C). - IR (KBr): 3538, 3498 (OH), 1693, 1662 cm^{-1} (C=O). - ^{1}H-NMR (80 MHz, $CDCl_3$, $CHCl_3$ int.[12]): δ = 0.80 (AA'BB', 4H), 1.50-3.00 (m, 19H), 7.00-7.30 (m, 5H). - ^{13}C-NMR (25.2 MHz, $CDCl_3$[12]): δ = 12.28, 16.17, 16.60, 24.38, 25.82, 30.24, 30.38, 38.50, 59.64, 60.21, 74.69, 127.03, 128.39, 130.89, 133.26, 207.76. - MS (70 eV): m/e = 396 (19%, M^+), 231 (100%). - $C_{24}H_{28}O_3S$ requires C, 72.70; H, 7.12; S, 8.09. Found: C, 72.98; H, 7.03; S, 8.19.

6-Phenylthiotetraspiro[3.0.3.0.3.1.3.1]octadec-6-ene-13,18-dione 11: A mixture of 4.50 g (11.4 mmol) **10** and 3.00 g (15.8 mmol) p-toluenesulfonic acid monohydrate in 300 ml of dry benzene was refluxed with azeotropic removal of water. Tlc analysis [CH_2Cl_2; R_f = 0.25 (**10**) and 0.45 (**11**)] indicated that the reaction was complete within 70 min. After cooling to room temperature the violet blue benzene solution was washed with saturated aqueous sodium bicarbonate solution (2 x 50 ml) and concentrated on a rotary evaporator (bath temperature 70°C/15 torr) to yield a brown residue which was dissolved in 30 ml of ether. Addition of pentane (50 ml) caused a precipitate which was discarded. Removal of the solvents and chromatography of the oily residue (4.1 g) on silica gel (0.05-0.20 mm) in dichloromethane (column 50 x 5 cm) yielded 2.62 g (61%) **11** as slightly yellowish oil which proved to be analytically pure but could be decolourized by treatment with activated charcoal in ether. - IR (film): 1711, 1681 cm^{-1} (C=O). - ^{1}H-NMR (80 MHz, $CDCl_3$, TMS int.): δ = 1.86 (d, J = 1.3 Hz, 2H), 1.90-2.25 (m, 18H), 6.06 (t, J = 1.3 Hz, 1H). - ^{13}C-NMR (25.2 MHz, $CDCl_3$[12]): δ = 15.90. 16.05, 26.54, 28.55, 30.33, 30.46, 32.59, 54.48, 57.60, 60.47, 126.32, 128.59, 129.33, 130.39, 133.53, 141.99, 210.04. - MS (70 eV): m/e = 378 (15%, M^+), 350 (M^+-C_2H_4), 241 (89%), 39 (100%). - $C_{24}H_{26}O_2S$ requires C, 76.15; H, 6.92; S, 8.47. Found: C, 75.86; H, 7.03; S, 8.56.

15-Ethyl-15-methyltrispiro[3.1.3.1.3.1]pentadecane-5,10-dione 12 and **tetraspiro[3.0.3.0.3.1.3.1]octadecane-13,18-dione 13**: W-7 Raney nickel[11] (70 g) was covered with absolute ethanol and, under stirring and nitrogen, a solution of 1.50 g (3.69 mmol) **11** in 3 ml of absolute ethanol was added at 80°C. The reaction was monitored by glpc [1.5m x 1/4" all-glass system, 15% OV 101 on chromosorb W AW/DMCS 60/80 mesh, 180°C; rel. retention times: 1.00, 1.23, 1.71 (**12**), 1.80 (**13**), 2.02 (**11**), 2.10, 2.50] and stopped, after **11** was completely consumed (10 min at 80°C). The mixture was filtered, the residue washed with ethanol (3 x 25 ml), and the combined filtrates concentrated on a rotary evaporator (bath temperature 80°C/15 torr) to yield 1.00 g (100%) of a yellowish oil. According to glpc analysis this oil consisted of **13** (60%), **12** (34%) and four compounds of unknown structure (6%). Analytically pure samples of **12** and **13** were obtained by preparative glpc, but for the synthesis of **14** the mixture was used as such.

12: colourless oil. - IR (film): 1710, 1680 cm^{-1} (C=O). - ^{1}H-NMR (200 MHz, $CDCl_3$, TMS int.): δ = 0.56 (t, J = 6.5 Hz, 3H), 0.69 (q, J = 6.5 Hz, 2H), 1.31 (s, 3H), 1.70-1.82 (m, 4H), 1.96-2.24 (m, 6H), 2.44-2.72 (m, 8H). - ^{13}C-NMR (50.3 MHz, $CDCl_3$, TMS int.): δ = 8.87, 15.14, 16.45, 16.78, 24.53, 25.98, 28.86, 29.03, 38.14, 40.23, 59.10, 59.79, 211.92. - MS (70 eV): m/e = 274 (44%, M^+), 246 (24%, M^+-C_2H_4), 245 (28%, M^+-C_2H_5), 217 (100%). - $C_{18}H_{26}O_2$ requires C, 78.79; H, 9.55. Found: C, 79.11; H, 9.54.

13: colourless oil. - IR (film): 1718, 1687 cm^{-1} (C=O). - ^{1}H-NMR (80 MHz, $CDCl_3$, $CHCl_3$ int.[12]): δ = 1.25-2.60 (m). - ^{13}C-NMR (50.3 MHz, $CDCl_3$, TMS int.): δ = 14.92, 15.82, 16.26, 24.52, 27.07, 29.57, 44.95, 56.56, 60.17, 211.46. - MS (70 eV): m/e = 272 (6%, M^+) 244 (48%, M^+-C_2H_4), 216 (100%). - Calculated for $C_{18}H_{24}O_2$: 272.1776. Found: 272.1773.

13,18-Dimethylenetetraspiro[3.0.3.0.3.1.3.1]octadecane 14: To a stirred suspension of 1.53 g (13.7 mmol) potassium t-butoxide in 12 ml of dry benzene under nitrogen was added 4.90 g (13.7 mmol) methyltriphenylphosphonium bromide and the mixture heated to reflux. After 1h the reaction temperature was reduced to 70°C and a solution of 0.88 g of a mixture of **12** and **13** containing 0.53 g (1.94 mmol) **13** in 1 ml of dry benzene was added. The reaction temperature was maintained at 70°C until a glpc analysis [3m x 1/4" all-glass system, 15% OV 101 on Chromosorb W AW/DMCS 60/80 mesh, 225°C; rel. retention times: 1.00 (**14**), 1.37 (**12**) and 1.47 (**13**)] indicated that the reaction was complete (7.5h). The mixture was cooled, diluted with 30 ml of pentane and hydrolyzed with 15 ml of water. The layers were separated, the organic layer washed with water (3 x 20 ml), the solvents distilled off and the residue extracted with 30 ml of cold pentane. The pentane extract was concentrated to give 0.66 g of a yellowish oil which was chromatographed on silica gel (0.05-0.20 mm; column 40 x 2.5 cm). Pentane eluted 206 mg (40%) of **14** as slowly crystallizing oil, dichloromethane 230 mg of unreacted **12**. Analytically pure **14** was obtained by crystallization from acetone as colourless crystals (mp 73-74°C). - IR (KBr): 1630, 1620 cm^{-1} (C=C). - ^1H-NMR (80 MHz, $CDCl_3$, TMS int.): δ = 1.60-2.40 (m, 24H), 5.04 (2s, 2H). - ^{13}C-NMR (50.3 MHz, $CDCl_3$[12]): δ = 14.20, 16.37, 17.17, 23.75, 28.60, 34.39, 50.93, 51.78, 53.37, 105.95, 145.45. - MS (70 eV): m/e = 240 (23%, M^+-C_2H_5), 197 (100%). - $C_{20}H_{28}$ requires C, 89.49; H, 10.51. Found: C, 89.59; H, 10.55.

Hexaspiro[2.0.3.0.2.0.3.0.3.0.3.0]docosane 6: To a stirred suspension of 2.0 g of freshly prepared zinc-silver couple[21] in 2 ml of anhydrous ether under nitrogen was added 100 mg (0.373 mmol) **14** and then 4.02 g (15.0 mmol) of diiodomethane at such a rate as to induce and maintain gentle reflux (30 min). After the exothermic reaction had subsided the mixture was heated to reflux until glpc analysis [3m x 1/4" all-glass system, 15% OV 210 on Chromosorb W AW/DMCS 60/80 mesh, 205°C; rel. retention times: 1.00 (**14**), 1.83 (**17**) and 3.19 (**6**)] indicated that the reaction was complete (3h). The mixture was hydrolyzed with 5 ml of saturated NH_4Cl_{aq} and then extracted with pentane (2 x 30 ml). The pentane extracts were concentrated and the remaining colourless oil (160 mg) chromatographed on silica gel (0.05-0.20 mm) in pentane (column 20 x 1 cm) to give 74 mg (65%) of **6** as colourless crystals (mp 237°C). - IR (KBr): 3075, 3010, 3000-2860 cm^{-1} (CH). - ^1H-NMR (100 MHz, $CDCl_3$, $CHCl_3$ int.[12], 25°C): δ = 0.05-2.60 (m). - ^{13}C-NMR (20.2 MHz, $CDCl_3$[12], 25°C): δ = 1.44, 5.97, 16.12, 16.28, 16.59, 23.78, 24.16, 24.96, 25.66, 26.60, 28.44, 33.36, 47.15, 48.21, 51.84. - MS (70 eV): m/e = 268 (3%, M^+-C_2H_4), 197 (100%). - $C_{22}H_{32}$ requires C, 89.12; H, 10.88. Found: C, 89.06; H, 10.85.

21-Methylenepentaspiro[3.0.3.0.3.0.3.0.3.1]heneicosane 16: To a stirred suspension of 7.69 g (68.5 mmol) potassium t-butoxide in 120 ml of dry benzene under nitrogen was added 24.5 g (68.6 mmol) methyltriphenylphosphonium bromide and the mixture heated to reflux. After 3h 70 ml of benzene were distilled off under nitrogen, a solution of 183 mg (0.613 mmol) **15**[9] in 6 ml of dry benzene was added, and the reaction mixture was further concentrated until the temperature of the remaining dark yellow slurry reached +135°C. This temperature was maintained until tlc analysis [CH_2Cl_2; R_f = 0.64 (**15**) and 0.80 (**16**)] indicated that the reaction was complete (65h). After cooling, the mixture was diluted with 40 ml of benzene and hydrolyzed with 200 ml of water. The aqueous phase was extracted with 20 ml of benzene and the combined benzene phases concentrated on a rotary evaporator (bath temperature 60°C/12 torr) to yield 16 g of a brown oil, which was dissolved in 60 ml of dichloromethane and then fixed on 30 g of added silica gel (0.2-0.5 mm) by evaporization of the solvent. This material was extracted with 600 ml of pentane in a soxleth-extractor (6h). Removal of the solvent gave 9.8 g of a light yellow oil which was chromatographed on silica gel (0.10-0.20 mm) in hexane (column 60 x 3.5 cm; control by tlc in hexane; R_f = 0.62) to yield 91 mg of a colourless solid, which was dissolved in 3.0 ml of boiling acetone and crystallized for 12h at 4°C and 6h at -18°C. 62 mg (34%) of pure **16** were obtained as colourless needles [mp 192-195 (capillary)]. - IR (KBr): 3096, 3027, 3001, 2994, 2945, 2859 (CH), 1621 cm^{-1} (C=C). - ^1H-NMR (100 MHz, C_6D_6, TMS int.): δ = 1.48-2.60 (m, 30H), 5.29 (s, 2H). - ^{13}C-NMR (20 MHz, C_6D_6, TMS int.): δ = 16.09, 16.55, 17.26, 24.97, 25.07, 25.98, 28.40, 29.40, 29.85, 49.51, 51.54, 53.30, 109.08, 149.87. - MS (70 eV): m/e = 296 (1%, M^+), 211 (100%). - Calculated for $C_{22}H_{32}$: 296.2504. Found: 296.2504.

Hexaspiro[2.0.3.0.3.0.3.0.3.0.3.0]tricosane 7: To a stirred suspension of 2.2 g of freshly prepared zinc-silver couple[21] in 1 ml of anhydrous ether under nitrogen was added 25.5 mg (0.086 mmol) **16** and 0.83 g (3.1 mmol) diiodomethane and the mixture heated to 60°C. The reaction was monitored by glpc [0.6m x 1/4" all-glass system, 12% FFAP on chromosorb W AW/DMCS 60/80 mesh, 220°C, 130 ml H_2/min; rel. retention times: 1.00 (**16**) and 1.62 (**7**)], after 30 min further 0.83 g (3.1 mmol) of diiodomethane were added, and after additional 20 min the reaction was complete. The mixture was diluted with 10 ml of ether, cooled to 0°C and carefully hydrolyzed with 10 mol of saturated NH_4Cl_{aq}. The liquid phases were decanted and the remaining zinc-silver slurry washed with 5 ml ether and 5 ml pentane. The organic phases were combined, washed with 5 ml of saturated $NaCl_{aq}$, dried over molecular sieves 4 Å and then concentrated to yield 43.3 mg of a yellowish solid which was chromatographed on silica gel (0.10-0.20 mm) in hexane (column 24 x 1.4 cm; control by tlc in hexane; R_f = 0.60) to give 25.9 mg of a colourless solid which was dissolved in 4 ml of boiling acetone and crystallized for 12h at 25°C, 24h at 4°C and 24h at -18°C. 20.2 mg (76%) of pure **7** were obtained as colourless prisms (mp 235-245°C). Concentration of the mother liquor to 0.3 ml and crystallization at -18°C yielded further 1.5 mg (6%) **7**. - IR (KBr): 3078, 2996, 2967, 2950, 2863 cm^{-1} (CH). - ^{1}H-NMR (200 MHz, $CDCl_3$, $CHCl_3$ int.$^{12)}$): δ = 0.51 (AA'BB', 4H), 1.42-2.06 (m, 18H), 2.07-2.38 (m, 6H), 2.42-2.70 (m, 6H). - ^{13}C-NMR (20 MHz, $CDCl_3$$^{12)}$): δ = -0.01, 6.89, 16.44, 16.52, 16.57, 21.36, 25.10, 25.43, 25.80, 27.46, 28.49, 28.93, 48.34, 49.58, 50.80. - MS (70 eV): m/e = 282 (3%, $M^+-C_2H_4$), 44 (100%). - $C_{23}H_{34}$ requires C, 88.96; H, 11.04. Found: C, 88.81; H, 11.12.

1,1-D_2-Hexaspiro[2.0.3.0.3.0.3.0.3.0]tricosane [1,1-D_2]-**7**: 34.4 mg (0.116 mmol) **16** were cyclopropanated as described for **7** using 2.2 g zinc-silver couple$^{21)}$ in 1.0 ml of anhydrous ether and 2 x 0.83 g (2 x 3.1 mmol) diiodomethane-$d_2$$^{22)}$. Work up and chromatography yielded 33.8 mg of a colourless solid which was crystallized from acetone to give 27.3 mg (75%) of pure [1,1-D_2]-**7** as colourless prisms (mp 232-245°C). - ^{1}H-NMR (200 MHz, $CDCl_3$, $CHCl_3$ int.$^{12)}$): δ = 0.44 (s, 1.33H), 0.56 (s, 0.67H), 1.39-2.67 (m, 30H). - ^{13}C-NMR (50.3 MHz, $CDCl_3$$^{12)}$): δ = -0.24, 6.65, 16.41, 16.49, 16.56, 21.13, 25.05, 25.39, 25.76, 27.43, 28.47, 28.89, 48.24, 49.51, 50.74. - MS (70 eV): m/e = 282 (9%, $M^+-CH_2D_2$; calculated for $C_{21}H_{30}$: 282.2347; found: 282.2347), 91 (100%).

18-Methylenetetraspiro[3.0.3.0.3.1.3.1]octadecane-13-one 17: To a stirred suspension of 1.04 g (9.3 mmol) potassium t-butoxide in 18.5 ml of dry benzene under nitrogen was added 3.32 g (9.3 mmol) methyltriphenylphosphonium bromide and the mixture heated to reflux. After 1h 2.40 g of a mixture of **12** and **13** containing 1.20 g (4.4 mmol) **13** was added and refluxing continued until glpc analysis [1.2m x 1/4" all-glass system, 15% OV 210 on Chromosorb W AW DMCS 60/80 mesh, 200°C, 120 ml H_2/min; rel retention times: 1.00 (**14**), 1.67 (**17**), 2.10 (**12**), 2.20 (**13**)] indicated that **13** was completely consumed (1h). The mixture was cooled, diluted with 30 ml of pentane and hydrolysed with 10 ml of water. The layers were seperated, the organic layer washed with water (3 x 10 ml), the aqueous phases extracted with pentane (10 ml), and the combined organic phases concentrated on a rotary evaporator (bath temperature 70°C/15 torr). The residue was dissolved in 10 ml of dichloromethane and fixed on 5 g of added silica gel (0.2-0.5 mm) by evaporization of the solvent. This material was extracted with 300 ml of pentane in a Soxhletextractor (10h). The pentane extract was cooled to 0°C for 1h, filtered and the filtrate concentrated on a rotary evaporator (bath temperature 70°C/15 torr) to yield 2.3 g yellow oil which was chromatographed on silica gel (0.10-0.20 mm) in dichloromethane [column 70 x 3.5 cm; control by tlc in dichloromethane; R_f = 0.36 (**12**), 0.56 (**17**) and 0.74 (**14**)] to give 810 mg (68%) of pure **17** as colourless oil which crystallized on cooling (mp 32-33°C). - IR (KBr): 1690 (C=O), 1625 cm^{-1} (C=C). - ^{1}H-NMR (100 MHz, $CDCl_3$, TMS int.): δ = 1.50-2.75 (m, 24H), 5.23 (s, 1H), 5.26 (s, 1H). - ^{13}C-NMR (50.3 MHz, $CDCl_3$, TMS int.): δ = 14.51, 16.24, 16.30, 16.44, 24.27, 27.78, 28.33, 33.07, 48.53, 50.89, 57.00, 57.30, 108.63, 152.61, 213.10. - MS (70 eV): m/e = 270 (2%, M^+), 242 (27, $M^+-C_2H_4$), 214 (100%). - $C_{19}H_{26}O$ requires C, 84.39; H, 9.69. Found: C, 84.49; H, 9.58.

Pentaspiro[2.0.3.0.3.0.3.1.3.0]eicosane-16-one 18: To 9.5 ml (30.4 mmol) of a 3.2-molar solution of ethylzinc iodide in ether$^{13)}$ under nitrogen was added 6.61 g (24.7 mmol) diiodomethane and the mixture heated to reflux. After 1h a solution of 400 mg (1.48 mmol) **17** in 3 ml of anhydrous ether was added and refluxing was continued until glpc analysis [1.2m x 1/4" all-glass system, 15% OV 210 on Chromosorb W AW/DMCS 60/80 mesh, 200°C, 120 ml H_2/min; rel. retention times: 1.00 (**17**) and 1.64 (**18**)] indicated that the reaction was complete (20.5h). The mixture was cooled to 0°C and hydrolyzed with 10 ml of water and 20 ml of 10% HCl. The layers were separated, the aqueous layer extracted with ether (2 x 10 ml), the combined organic phases washed with saturated sodium thiosulphate and then with water, dried (Na_2SO_4) and concentrated to yield 2.0 g of a yellow oil. Chromatography on silica gel (0.10-0.20 mm) in dichloromethane (column 30 x 3 cm; control by tlc in dichloromethane; R_f = 0.57) yielded 300 mg (71%) of pure **18** as colourless oil which crystallized on cooling (mp 66-67°C). - IR (KBr): 1683 cm^{-1} (C=O). - ^{1}H-NMR (100 MHz, $CDCl_3$, $CHCl_3$ int.$^{12)}$): δ = 0.47 (AA'BB', 4H), 1.4-2.7 (m, 24H). - ^{13}C-NMR (50.3 MHz, $C_6D_6$$^{12)}$): δ = 4.81, 15.96, 16.68, 17.34, 17.39, 25.27, 26.63, 27.00, 28.78, 30.80, 47.02, 52.41, 55.88, 58.76, 211.65. - MS (70 eV): m/e = 284 (8%, M^+), 200 (100%). - $C_{20}H_{28}O$ requires C, 84.45; H, 9.92. Found: C, 84.37; H, 9.78.

16-Methylene-^{13}C-pentaspiro[2.0.3.0.3.0.3.1.3.0]eicosane [methylene-^{13}C]-**19**: To a stirred suspension of 268 mg (2.36 mmol) potassium t-butoxide in 2.4 ml of dry benzene under nitrogen was added 970 mg (2.36

mmol) of ^{13}C-methyltriphenylphosphonium iodide[23] and the mixture heated under reflux. After 1h 279 mg (0.982 mmol) **18** was added and the mixture concentrated under nitrogen until the temperature of the remaining dark yellow slurry reached +130°C. This temperature was maintained until glpc analysis [1.2m x 1/4" all-glass system, 15% OV 210 on Chromosorb W AW/DMCS 60/80 mesh, 200°C, 120 ml/H_2/min; rel. retention times: 1.00 ([methylene-^{13}C]-**19**) and 1.74 (**18**)] indicated that the reaction was complete (4.5h). The mixture was cooled, diluted with 2.5 ml of pentane and hydrolyzed with 240 μl of water. The organic layer was decanted and the heterogeneous residue extracted with pentane (3 x 1 ml). The organic phases were combined, washed with water (3 x 1 ml) and concentrated to yield 340 mg of a yellow oil. Chromatography on silica gel (0.10-0.20 mm) in pentane [column 30 x 1.5 cm; control by tlc in pentane; R_f = 0.51)] yielded 224 mg (80%) of pure [methylene-^{13}C]-**19** as colourless solid (mp 162°C). - IR (KBr): 1608 cm^{-1} (C=C). - ^{1}H-NMR (200 MHz, $CDCl_3$, $CHCl_3$ int.[12]): δ = 0.44 (AA'BB', 4H), 1.5-2.5 (m, 24H), 5.01 (dd, J_{CH} = 154.2 Hz, J_{HH} = 0.8 Hz, 1H), 5.10 (dd, J_{CH} = 154.7 Hz, J_{HH} = 0.8 Hz, 1H). - MS (70 eV): m/e = 255 (M^+-C_2H_4), 213 (100%).

1-^{13}C-Hexaspiro[2.0.3.0.2.0.3.0.3.0.3.0]docosane [1-^{13}C]-**6**: To a stirred suspension of 8.0 g freshly prepared zinc-silver couple[21] in 8 ml of anhydrous ether under nitrogen was added 15.9 g (59.3 mmol) diiodomethane at such a rate as to induce and maintain gentle reflux (45 min). A solution of 202 mg (0.71 mmol) [methylene-^{13}C]-**19** in 2.0 ml of anhydrous ether was added and refluxing continued by external heating. The reaction was monitored by glpc [1.2m x 1/4" all-glass system, 15% OV 210 on Chromosorb W AW/DMCS 60/80 mesh, 200°C, 120 ml H_2/min; rel. retention times: 1.00 ([methylene-^{13}C]-**19**) and 1.61 ([1-^{13}C]-**6**)] and stopped after [methylene-^{13}C]-**19** was completely consumed (30 min). The mixture was diluted with 25 ml of ether and carefully hydrolyzed with 10 ml of saturated NH_4Cl_{aq}. The liquid phases were decanted and the remaining zinc-silver slurry washed with 10 ml of ether and 10 ml of pentane. The organic phases were combined, washed with 10 ml of $NaCl_{aq}$, dried over molecular sieves 3 Å and concentrated to yield 8.2 g of a yellow oil which was chromatographed on silica gel (0.10-0.20 mm) in pentane (column 32 x 3 cm; control by tlc in pentane; R_f = 0.58) to yield 165 mg (78%) of pure [1-^{13}C]-**6** as colourless solid (mp 210-219°C) and 110 mg of impure material which was chromatographed as above and gave a second crop of 31 mg (14%) of pure [1-^{13}C]-**6**. Combined yields: 196 mg (92%).

Crystal structure analysis of 6: **6** (molecular formula $C_{22}H_{32}$, M = 296.5) was crystallized from acetone as colourless prisms, space group $P2_1/m$, $\underline{a}$ = 8.212(1), $\underline{b}$ = 13.580(2), $\underline{c}$ = 7.644(1) Å, $\underline{\beta}$ = 93.98(1)°, $\underline{V}$ = 850.4 $Å^3$, $\underline{Z}$ = 2, $\underline{D}_c$ = 1.158 $g \cdot cm^{-3}$. 1558 reflections with $2\Theta_{max}$ = 50° were measured on a Stoe four-circle diffractometer using graphite-monochromated Mo-K_α radiation; of these, 1169 with $|F| > 3\sigma_F$ were used for the structure determination and refinement. The structure was solved by direct methods and refined isotropically to R = 0.197, which dropped to R = 0.129 with inclusion of anisotropic temperature factors. At this stage all H atoms were located by a difference electron-density synthesis. Anisotropic refinement with fixed individual H atom temperature factors finally converged at R = 0.063 (R_w = 0.062, $w^{-1} = \sigma_F^2 + 0.0005 \cdot F^2$). C atom parameters are listed in Table 7[24].

	$\underline{x}$	$\underline{y}$	$\underline{z}$	$\underline{U}^*$		$\underline{x}$	$\underline{y}$	$\underline{z}$	$\underline{U}^*$
C(1)	-373(3)	1182(2)	1276(3)	56(1)	C(16)	2776(4)	2500	-675(4)	57(1)
C(2)	-219(4)	628(2)	2952(4)	66(1)	C(17)	4597(5)	2500	-1223(5)	79(2)
C(3)	687(2)	1592(1)	2655(3)	40(1)	C(18)	4995(4)	2500	699(5)	64(1)
C(4)	66(3)	2500	3661(4)	41(1)	C(19)	2544(2)	1552(2)	2270(3)	40(1)
C(5)	347(4)	2500	5668(4)	59(1)	C(20)	3210(4)	592(2)	1333(4)	60(1)
C(6)	-1431(5)	2500	6135(5)	83(2)	C(21)	4102(4)	305(2)	2960(4)	70(1)
C(7)	-1809(4)	2500	4253(5)	62(1)	C(22)	3512(3)	1240(2)	3898(3)	52(1)
C(15)	3138(3)	2500	1314(4)	40(1)					

*Equivalent isotropic $\underline{U}$ defined as one third of the trace of the orthogonalized $\underline{U}_{ij}$ tensor

Table 7. Atomic coordinates ($\cdot 10^4$) and equivalent isotropic displacement parameters ($Å^2 \cdot 10^3$) for **6** with estimated standard deviations in parentheses

Crystal structure analysis of 7: **7** (molecular formula $C_{23}H_{34}$, M = 310.5) was crystallized from acetone as colourless prisms, space group $P\bar{1}$, $\underline{a}$ = 7.830(1), $\underline{b}$ = 7.975(1), $\underline{c}$ = 8.154(1) Å, $\underline{\alpha}$ = 70.17(1), $\underline{\beta}$ = 73.16(2), $\underline{\gamma}$ = 75.17(1)°, $\underline{V}$ = 451.4 $Å^3$, $\underline{Z}$ = 1, $\underline{D}_c$ = 1.142 $g \cdot cm^{-3}$. 1745 reflections with $2\Theta_{max}$ = 50° were measured on a Stoe four-circle diffractometer using graphite-monochromated Mo-K_α radiation; of these, 1238 with $|F| > 3\sigma_F$ were used for the structure determination and refinement. The structure was solved by direct methods and refined isotropically to R = 0.178, which dropped to R = 0.139 with inclusion of anisotropic temperature factors. At this stage most H atoms were located by a difference electron-density synthesis. Weights $w = (\sigma_F^2 + 0.001 \cdot F^2)^{-1}$ were introduced, and further anisotropic refinement with geometrically positioned H atoms (riding-model: r_{C-H} = 0.96 Å, $\sphericalangle$ HCH = 109.5°) and fixed individual temperature factors $[U(H) = 1.2 \cdot U_{eq}(C)]$ finally converged at $R = 0.071$ ($R_w = 0.080$). The molecule lies twofold disordered on a centre of symmetry. Therefore, site occupation factors of 0.5 were assigned to C(1), C(2), C(13), C(14), C(15) and the corresponding H atoms. Moreover, the bond lengths of the cyclopropane ring had to be restrained [1.52(2) Å] to ensure convergence. C atom parameters are listed in Table 8[24]. All calculations were performed with the program SHELXTL.

	x	y	z	U*		x	y	z	U*
C(1)	2690(20)	3640(19)	8679(15)	131(9)	C(13)	7013(14)	5988(16)	1124(11)	46(3)
C(2)	2479(21)	3094(22)	7127(21)	85(7)	C(14)	8412(7)	7084(9)	1236(9)	57(3)
C(3)	3818(3)	4285(3)	6774(3)	43(1)	C(15)	7527(16)	6929(19)	3275(18)	49(3)
C(4)	3402(3)	6276(3)	5664(3)	43(1)	C(20)	5842(3)	3462(3)	6344(3)	44(1)
C(5)	1364(3)	7199(3)	6143(4)	68(1)	C(21)	6329(4)	1475(3)	7536(4)	71(1)
C(6)	1862(4)	8562(4)	6705(5)	95(2)	C(22)	7397(5)	2033(5)	8428(5)	97(2)
C(7)	3815(3)	7680(3)	6392(4)	62(1)	C(23)	7021(3)	3960(3)	7306(3)	64(1)

*Equivalent isotropic U defined as one third of the trace of the orthogonalized U_{ij} tensor

Table 8. Atomic coordinates ($\cdot 10^4$) and equivalent isotropic displacement parameters ($Å^2 \cdot 10^3$) for **7** with estimated standard deviations in parentheses

Kinetic measurements: ^1H- and ^{13}C-NMR spectra were recorded on a Varian XL 200 spectrometer equipped with a variable temperature probe. Temperatures were measured with a temperature sensor consisting of a 1.8 mm diameter high precision PT 100 resistor (1/5 DIN; accuracy ±0.05°C from 0°C to +200°C) at the end of a glass rod which was introduced in a 5 mm o.d. dummy tube containing pure nitrobenzene-d_5 such, that the active zone (15 mm length) was precisely positioned at the height of the receiver coil. During both equilibrations the temperatures were precise within ± 0.5°C. Precision 5 mm o.d. NMR tubes (No. 507 PP, Wilmad Glass Co.) were filled with solutions of 33 mg $[1\text{-}^{13}C]_{a,e}$-**6** and 10 mg $[1,1\text{-}D_2]_{a,e}$-**7**, respectively, in 500 µl of nitrobenzene-d_5 and the decrease in concentration of $[1\text{-}^{13}C]_a$-**6**[16] and $[1,1\text{-}D_2]_e$-**7**[16] was followed by ^{13}C-NMR (50.3 MHz, 80 transients, acquisition time 1.501 sec, pulse width 30°) at +66.0°C and ^1H-NMR (200 MHz, 16 transients, acquisition time 3.077 sec, pulse width 30°) at +150.0°C, respectively. The spectra were taken at appropriate times (Fig.2) and the initial (I_o) and actual concentrations (I) determined by careful integration of the corresponding resonance lines of the cyclopropane ring (Fig.1). To ensure complete equilibration, the solutions of $[1\text{-}^{13}C]_{a,e}$-**6** and $[1,1\text{-}D_2]_{a,e}$-**7** used in the kinetic analyses were finally heated for 24h to +100°C and 16h to +150°C, respectively until the equilibrium concentrations (I_e) were determined by four independent measurements in each case. The following values were obtained: $I_e([1\text{-}^{13}C]_a$-**6**$) = 49.80 \pm 0.36$ and $I_e([1,1\text{-}D_2]_e$-**7**$) = 50.14 \pm 0.14$. Because of the unfavourable error situation values of $I_e = 50.00$ were used in both cases instead.

Calculations: The weighted least-squares adjustments of the rate data were performed on the Sperry Univac 1100 computer of the Gesellschaft für Wissenschaftliche Datenverarbeitung at Göttingen, employing the computer program ACTPAR[25].

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15) For this purpose, unlabeled **19** (**16**) will be reacted with dibromocarbene and one of the resulting conformational isomers of $[1,1\text{-}Br_2]_{a,e}$-**6** ($[1,1\text{-}Br_2]_{a,e}$-**7**) submitted to a crystal structure analysis. Thus identified as $[1,1\text{-}Br_2]_a$-**6** or $[1,1\text{-}Br_2]_e$-**6** ($[1,1\text{-}Br_2]_a$-**7** or $[1,1\text{-}Br_2]_e$-**7**), this material will be reduced under non-equilibrating conditions to the corresponding conformational isomer of $[1,1\text{-}D_2]_{a,e}$-**6** ($[1,1\text{-}D_2]_{a,e}$-**7**). A comparision of the ^{13}C-NMR data with those of $[1\text{-}^{13}C]_{a,e}$-**6** ($[1,1\text{-}D_2]_{a,e}$-**7**) will then allow an unambiguous assignment. Research along these lines is in progress.

16) Tentative assignment; for an unambiguous assignment see[15].

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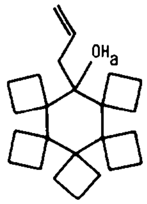
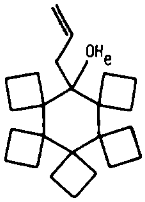
18) Because of the unfavourable error situation in the determination of the equilibrium concentrations of $[1\text{-}^{13}C]_a$-**6** (I_e = 49.80 ± 0.36) and $[1,1\text{-}D_2]_e$-**7** (I_e = 50.14 ± 0.14; see experimental part) no isotope effects could be detected.

19) The only two other cyclohexanes where conformational isomerism at room temperature has been observed are **22a** (ΔG^{*}_{413} = 134.9 kJ/mol)[1] and **22b** (ΔG^{*}_{413} = 136.9 kJ/mol)[1]. Their barriers of inversion are nearly identical to that of $[1,1\text{-}D_2]_{a,e}$-**7** (ΔG^{*}_{423} = 136.0 kJ/mol), and it is interesting to note that in all three cyclohexanes only one alternation is present.

22a





22b

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23) Methyl-^{13}C-triphenylphosphonium iodide (99 atom % ^{13}C; mp 176°C) was obtained by reacting triphenylphosphine (70 mmol) in dry benzene (60 ml) with methyl-^{13}C iodide (70 mmol, 99 atom % ^{13}C) for 72h at r.t. (yield 98%).

24) All relevant crystallographic data have been deposited with the Cambridge Crystallographic Database via the Fachinformationszentrum Energie, Physik, Mathematik, D-7514 Eggenstein-Leopoldshafen 2 (CSD-52640).

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