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STERICALLY CROWDED CYCLOHEXANES - 10.[1] SYNTHESIS, CONFORMATION AND DYNAMICS OF 8,8,13,13-TETRAMETHYLTETRASPIRO[2.0.3.1.3.1.3.0]HEPTADECANE

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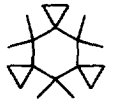
Abstract: The synthesis, conformation and dynamics of 8,8,13,13-tetramethyltetraspiro[2.0.3.1.3.1.-3.0]heptadecane (**11**) are described. **11** adopts a chair conformation in solution. Its barrier of inversion proved inaccessible by DNMR but could be determined from equilibration studies with stereoselectively labeled [1-^{13}C]$_e$-**11**. The results were as follows: $\Delta H^{\neq}$ = 104.7 kJ/mol, $\Delta S^{\neq}$ = -13.1 J/mol·K and $\Delta G^{\neq}_{298}$ = 108.6 kJ/mol. The stereoisomers of [1-^{13}C]$_{e,a}$-**11** thus represent a further case of conformational isomerism within the cyclohexane family. © 1997 Elsevier Science Ltd.

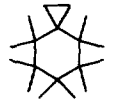
Introduction

The conformation and dynamics of fully substituted cyclohexanes is dominated by strong nonbonding interactions. As a consequence, an unusual accumulation of anomalies has been observed. Illustrative are the cyclohexanes **1-8**. Of these, five (**3**,[2] **4**,[2,3] **6**,[4] **7**,[4] **8**[5]) adopt a chair conformation, one (**5**[6]) prefers a chair-to-twistboat equilibrium, and two (**1**,[7] **2**[7]) exist in a pure twistboat conformation. Interestingly, all barriers of inversion largely exceed the normal range of 0-5 and 40-50 kJ/mol for twistboat-to-twistboat and chair-to-chair interconversions, respectively. Barriers up to 58.1 kJ/mol for twistboat-to-twistboat inversions (**2**), and 156.8 kJ/mol for chair-to chair inversions (**8**) have been observed. With **6**, **7** and **8**, the barriers of inversion exceed 100 kJ/mol. In these cases, conformational isomerism[8,9] has been observed.



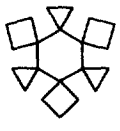
1
twistboat
19.7

2
twistboat
58.1

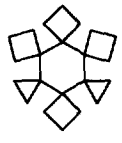


3
chair
67.2

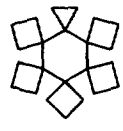
4
chair
72.4



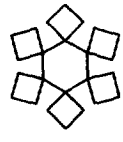
5
twistboat 35.9
chair 92.0



6
chair
112.2

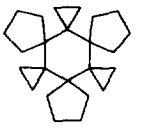


7
chair
136.0



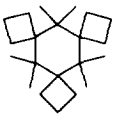
8
chair
156.8

Concerning the conformation adopted, the following rules seem to apply: (a) substitution with substituents of identical opening angles as in **4** and **8** favours a chair conformation, (b) substitution with substituents of strongly alternating opening angles as in **1** favours a twistboat conformation, and (c) substitution with substituents of moderately alternating opening angles as in **5** falls in between. After a first test with hexaspirane **9**[1] favouring a twistboat had been successful, we envisaged a second test with trispirane **10**. We herein report on an attempted synthesis via tetraspirane **11**, and on an investigation of this interesting cyclohexane, representing a further case of conformational isomerism within the cyclohexane family.

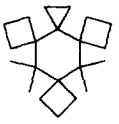


9

twistboat < 24.0
chair 67.6



10

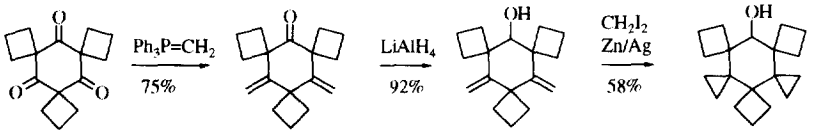


11

Syntheses

In principle, trispirane **10** could have been accessible by hydrogenation of hexaspirane **5**. However, with fully substituted cyclohexanes containing more than one spiroanellated cyclopropane ring, rearrangements during hydrogenations have been observed.[7a] Therefore, the most appropriate precursor of trispirane **10** was tetraspirane **11**.

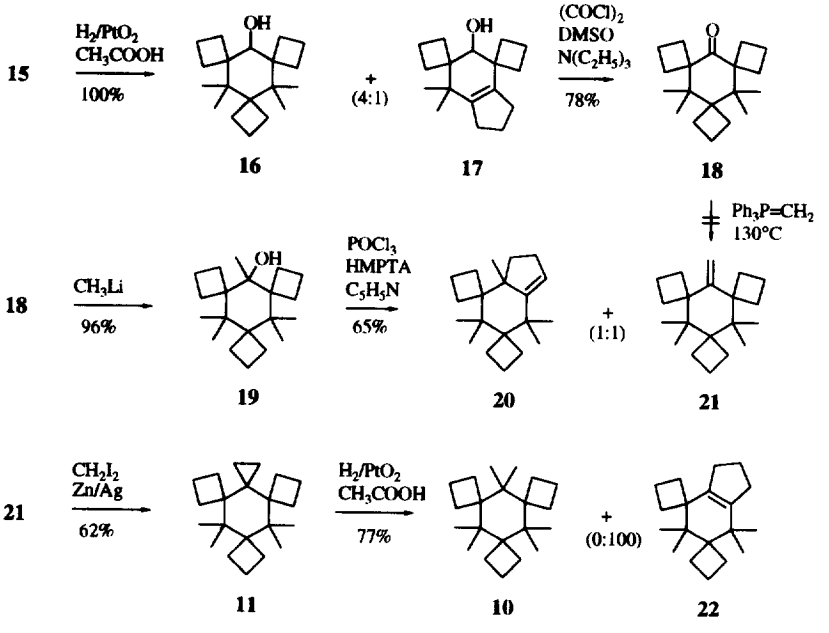
We started our synthesis of tetraspirane **11** with dienone **13**,[10] readily available by selective dimethylenation of trione **12**.[11] Reduction with lithium aluminium hydride yielded the dienol **14**, and subsequent cyclopropanation using a modified Simmons-Smith reaction[12] yielded the pentaspirane **15**.



12 **13** **14** **15**

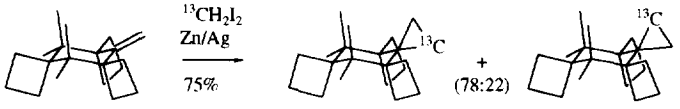
During the following hydrogenation over platinium dioxide in acetic acid a substantial amount of **15** reacted with cleavage of a lateral cyclopropane bond followed by ring enlargement of a cyclobutane ring and loss of ethylene to give the bicyclononene **17**. Fortunately, after one crystallisation the desired tetramethylated cyclohexanol **16** was pure. Of the remaining three steps - a Swern oxidation[13] to **18**, a methylenation to **21** and a cyclopropanation to **11** - the methylenation proved difficult. After all attempts of a direct methylenation using a high temperature modification[14] of the Wittig reaction had failed, ketone **18** was treated with methyllithium and the resulting tertiary alcohol **19** treated with phosphorous oxychloride and pyridine in hexamethylphosphorous triamide[15] to achieve elimination. Once again, concomitant rearrangement occurred and half of

the material was lost through formation of bicyclononene **20**.[16] This time, the desired trispirane **21** had to be separated by chromatography on silica gel impregnated with silver nitrate, but could be cyclopropanated without difficulties to give the tetraspirane **11**.



To our disappointment, the hydrogenation of **11** delivered no trispirane **10**. Instead, exclusive opening of a lateral cyclopropane bond occurred, and ring enlargement of a cyclobutane ring and loss of ethylene completed the formation of the undesired bicyclooctene **22**. However, tetraspirane **11** proved to be extremely interesting itself. At room temperature, the ^{13}C NMR spectrum (50 MHz, $CDCl_3$, $CDCl_3$ int) showed fourteen resonances indicating that the preferred conformation in solution is a fixed chair (symmetry C_s). A rapidly interconverting species (effective symmetry C_{2h}) would have shown ten resonances, and a fixed twistboat either twelve (symmetry C_2) or twenty-one (symmetry C_1). As the ^1H NMR spectrum (80 MHz, $C_6D_5NO_2$, $C_6D_5NO_2$ int) of **11** remained unchanged up to 190°C, an inversion barrier distinctly above 100 kJ/mol could be expected and the necessity of equilibration studies with stereoselectively labeled material became obvious.

For the synthesis of stereoselectively labeled [1-^{13}C]-**11**, we treated olefin **21** with an excess of ^{13}C-diiodomethane in a modified Simmons-Smith reaction.[12] Indeed, two ^{13}C-resonances at $\delta = 2.39$ and 10.98 with an intensity ratio of 78:22 indicated that the cyclopropanation had been stereoselective and that the stereochemistry had been preserved by a sufficiently high barrier of inversion. Assuming a perferential equatorial attack of the reagent, [1-^{13}C]$_e$-**11** had formed in excess.[17]



21 [1-^{13}C]$_e$-**11** [1-^{13}C]$_a$-**11**

Dynamics

Preliminary measurements revealed that the equilibration of the stereoisomers of [1-^{13}C]-**11** could most conveniently be followed by ^{13}C NMR spectroscopy (126 MHz, $C_6D_5NO_2$) at 65°C. In order to obtain the full set of activation parameters ($\Delta H^{\neq}$, $\Delta S^{\neq}$, $\Delta G^{\neq}_{298}$), the equilibration was followed at three different temperatures (58.0, 65.0 and 70.0°C). The spectra were taken at appropriate times and the concentration of [1-^{13}C]$_a$-**11** [$I_{ax}/(I_{ax}+I_{equ})$] determined by measuring the intensities of the resonance lines of [1-^{13}C]$_a$-**11** (I_{ax}) and [1-^{13}C]$_e$-**11** (I_{eq}). The equilibration followed first order kinetics. The weighted least-squares approximations of $\ln[(I_o-I_e)/(I-I_e)] = [k([1\text{-}^{13}C]_a\text{-}\mathbf{11}) + k([1\text{-}^{13}C]_e\text{-}\mathbf{11}]\cdot t$, with I_o, I and I_e referring to the initial, actual and equilibrium concentrations of [1-^{13}C]$_a$-**11**, respectively, shown graphically in Figure 1, yielded the following rate constants at the three temperatures employed: k (58°C) = 4.218 ± 0.045 [10^{-5} s^{-1}], k (65°C) = 9.903 ± 0.157 [10^{-5} s^{-1}], and k (70°C) = 16.300 ± 0.030 [10^{-5} s^{-1}]. A weighted adjustment of the rate data to the Eyring equation, shown graphically in Figure 2, yielded the activation parameters and their standard deviations as $\Delta H^{\neq}$ = (104.7 ± 5.5) kJ/mol and $\Delta S^{\neq}$ = (-13.1 ± 16.3) J/mol·K. The free energy of activation was then calculated from the equation $\Delta G^{\neq} = \Delta H^{\neq} - T\Delta S^{\neq}$ to give $\Delta G^{\neq}_{298}$ = (108.6 ± 10.4) kJ/mol. All calculations were performed with the computer program ACTPAR.[18]

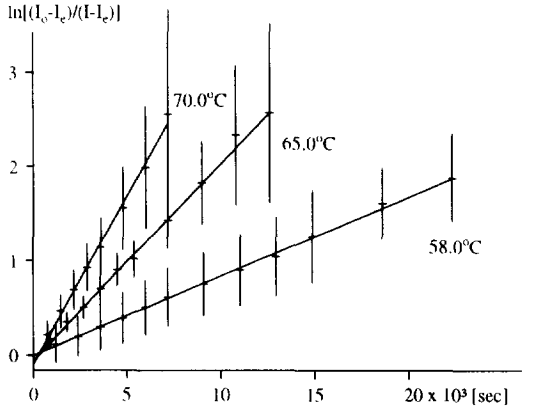


Figure 1. Least-squares approximations of $\ln[(I_o-I_e)/(I-I_e)] = [k([1\text{-}^{13}C]_e\text{-}\mathbf{11}) + k([1\text{-}^{13}C]_a\text{-}\mathbf{11})]\cdot t$. I_o, I and I_e refer to the initial, actual, and equilibrium concentrations of [1-^{13}C]$_a$-**11**, respectively.

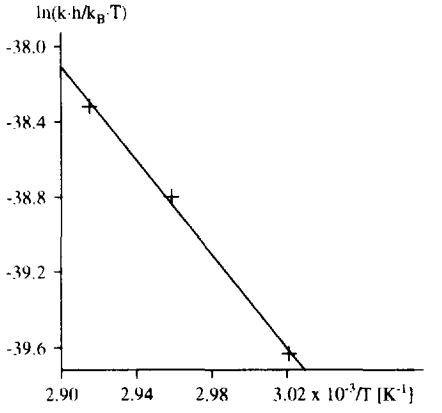


Figure 2. Adjustment of the rate data to the Eyring equation.

Summary and Conclusion

8,8,13,13-Tetramethyltetraspiro[2.0.3.1.3.1.3.0]heptadecane (**11**) adopts a fixed chair conformation in solution and represents one of the rare cases of conformational isomerism within the cyclohexane family. Its barrier of inversion proved inaccessible by DNMR but could be determined from equilibration experiments with stereoselectively labeled [1-^{13}C]-**11**. The results were as follows: $\Delta H^{\neq}$ = (104.7 ± 5.5) kJ/mol, $\Delta S^{\neq}$ = (-13.1 ± 16.3) J/mol·K, and $\Delta G^{\neq}_{298}$ = (108.6 ± 10.4) kJ/mol. The negative activation entropy indicates that the transition state of the chair-to-chair interconversion is highly ordered. All attempts to hydrogenate tetraspirane **11** to trispirane **10** as a promising candidate for a cyclohexane in twistboat conformation failed. Opening of a lateral cyclopropane bond followed by rearrangement and extrusion of ethylene yielded the bicyclononene **22**. An analogous reaction was observed during the hydrogenation of **15**. Obviously, steric overcrowding in fully substituted cyclohexanes renders rearrangements and fragmentations to common processes.

EXPERIMENTAL

IR spectra were recorded on a Perkin-Elmer 298 spectrophotometer. ^{1}H and ^{13}C NMR spectra were measured on a Varian FT 80A, XL 200, VXR 200 or VXR 500 spectrometer. For standards other than TMS the following chemical shifts were used: $\delta_H(CHCl_3)$ = 7.24, $\delta_C(CDCl_3)$ = 77.00, $\delta_C(C_6D_6)$ = 128.00 and $\delta_C(C_6D_5NO_2)$ = 129.50 (C-3,5). Mass spectra were obtained with a Varian MAT 311 A or 701 instrument operated at 70 eV. Analytical and preparative gas chromatography was carried out on a Carlo Erba 6130 FID 40 and an Intersmat IGC 16 instrument, respectively, with hydrogen as carrier gas. Product ratios were not corrected for relative response. R_f values are quoted for Macherey & Nagel Polygram SIL G/UV$_{254}$ plates. Colourless substances were detected by oxidation with 3.5% alcoholic 12-molybdophosphoric acid and subsequent warming. Impregnated tlc plates were prepared by dipping the plates into a solution of 10% (w/w) silver nitrate in methanol/water (2:1, v/v) and drying for 1 h at 110°C.[19] The silica gel impregnated with silver nitrate for column chromatography was prepared by adding the appropriate amount of silica gel to a solution of silver nitrate in acetonitrile, evaporating the solvent on a rotary evaporator, and drying the residue for 48 h at 80°C/0.5 torr, prior to use. Melting points are not corrected.

5,10-Dimethylene-trispiro[3.1.3.1.3.1]petadecan-15-ol (14): To a stirred solution of lithium aluminium hydride (2.07 g, 55 mmol) in anhydrous ether (100 ml) under nitrogen was added a solution of **13**[10] (6.05 g, 25 mmol) in anhydrous ether (30 ml) and the mixture heated to reflux. After 1 h, the reaction was complete according to tlc analysis [pentane; R_f = 0.42 (**13**), 0.16 (**14**)]. The mixture was hydrolyzed by succesive addition of water (2.03 ml), 15% aqueous sodium hydroxide (2.03 ml) and water (5.91 ml),[20] filtrated, and the residue extracted with ether. The combined organic layers were concentrated on a rotary evaporator (bath temperature 20°C/20 torr) to give 5.56 g (92%) of pure **14** as colourless crystals (mp 46-51°C). IR (KBr) O-H 3520, O-H$_{ass}$ 3500-3350 cm^{-1}; ^{1}H NMR (80 MHz, $CDCl_3$, TMS int) 0.85 (d, 1H, J = 10 Hz, D_2O exchange), 1.55-2.55 (m, 18H), 3.98 (d, 1H, J = 10 Hz), 4.98 (s, 2H), 5.08 (s, 2H); ^{13}C NMR (20 MHz, $CDCl_3$, TMS int) 16.57, 17.04, 29.80, 30.28, 33.43, 34.92 (C_{sek}), 50.91, 52.61 (C_{quart}), 80.02 (C_{tert}), 107.49 (C_{sek}), 153.91 (C_{quart}); MS m/z 216 (M^+-28, 80), 188 (100). Anal. calcd for $C_{17}H_{24}O$: C, 83.55; H, 9.90. Found: C, 83.69; H, 9.98.

Pentaspiro[3.0.2.0.3.0.2.0.3.1]nonadecan-19-ol (15): To a stirred suspension of freshly prepared zinc-silver couple[12] (34.0 g) in anhydrous ether (250 ml) under nitrogen was added a solution of **14** (5.56 g, 23 mmol) in anhydrous ether (60 ml) followed by diiodomethane (61.0 g, 228 mmol). After the vigorous reaction had subsided, the mixture was heated to reflux until glpc analysis [1.8 m x 1/4" all glass system, 15% SE 30 on Chromosorb W AW/DMCS 60/80 mesh, 220°C; rel. retention times: 1.00 (**14**), 2.00 (**15**)] indicated that the reaction was complete (3.5 h). The mixture was hydrolyzed with saturated ammonium chloride (25 ml) and filtrated. The filtrate was successively washed with water, saturated sodium thiosulfate and water, dried over magnesium sulfate and concentrated on a rotary evaporator (bath temperature 20°C/20 torr) to give 7.02 g of a yellow oil. Chromatography on silica gel (0.05-0.20 mm) in dichloromethane [column 45 x 3 cm; R_f = 0.58 (**15**)] yielded 3.62 g (58%) of pure **15** as colourless solid. The ^{1}H NMR data were identical with those of authentic material.[10]

5,5,10,10-Tetramethyltrispiro[3.1.3.1.3.1]pentadecan-15-ol (16) and 5,5-Dimethyl-dispiro[bicyclo-[4.3.0]non-1(6)-en-3-ol-2,1´:4,1´´-biscyclobutane] (17): To a solution of **15** (1.00 g, 3.70 mmol) in glacial acetic acid (7.0 ml) was added platinium dioxide (355 mg) and the mixture hydrogenated at 45-50°C and 1.1 atm hydrogen pressure in a shaking gear until glpc analysis [1.8 m x 1/4" all glass system, 15% OV 210 on Chromosorb W AW/DMCS 60/80 mesh, 220°C; rel. retention times: 1.00 (**17**), 1.08, 1.17 (**16**)] indicated that the product distribution (15% **17**, 20%, 65% **16**) remained constant (8 h). The mixture was filtrated and the filtrate diluted with water (25 ml) and extracted with pentane (3 x 25 ml). The extracts were washed with saturated sodium bicarbonate (3 x 10 ml), dried over magnesium sulfate and concentrated on a rotary evaporator (bath temperature 20°C/20 torr) to give a colourless solid (880 mg). This material was dissolved in glacial acetic acid (7.0 ml) and hydrogenated over platinium dioxide (200 mg) as described above until glpc analysis indicated that the product distribution (20% **17**, 80% **16**) remained constant (10.5 h). Work up and crystallisation from pentane yielded 643 mg (63%) of pure **16** as colourless solid (mp 90-98°C). The mother liquor was concentrated and the residue chromatographed on silica gel (0.05-0.20 mm) in pentane/ether [9:1, column 38 x 2 cm; R_f = 0.28 (**16**), 0.24 (**17**)] to give 41 mg (5%) of pure **17** as colourless oil. **16:** IR (KBr) O-H 3620, O-H_{ass} 3600-3300 cm^{-1}; ^{1}H NMR (200 MHz, $CDCl_3$, $CHCl_3$ int) 0.65 (s, 6H), 1.44 (s, 6H), 1.60-2.44 (m, 19H), 3.50 (d, 1H, J = 6 Hz); ^{13}C NMR (20 MHz, $CDCl_3$, $CDCl_3$ int) 15.23, 16.61 (C_{sek}), 21.44 (C_{prim}), 22.27 (C_{sek}), 23.28 (C_{prim}), 25.36, 25.71, 27.64 (C_{sek}), 40.77, 50.35, 51.42 (C_{quart}), 74.77 (C_{tert}); MS m/z 41 (100). Anal. calcd for $C_{19}H_{32}O$: C, 82.55; H, 11.67. Found: C, 82.25; H, 11.40. **17:** ^{1}H NMR (80 MHz, $CDCl_3$, $CHCl_3$ int) 0.85 (s, 3H), 1.15 (s, 3H), 1.25-2.75 (m, 19H), 3.55 (br s, 1H); ^{13}C NMR (20 MHz, $CDCl_3$, $CDCl_3$ int) 15.30, 17.08, 21.17, 22.09 (C_{sek}), 22.92, 23.13 (C_{prim}), 23.59, 26.56, 29.66, 31.95, 32.23 (C_{sek}), 37.57, 45.02, 49.11 (C_{quart}), 78.59 (C_{tert}), 136.69, 138.88 (C_{quart}); MS m/z 246 (M^+, 12), 218 (100). HRMS m/z (M^+) calcd 246.19837, obsd 246.19837.

5,5,10,10,15,-Tetramethyltrispiro[3.1.3.1.3.1]pentadecan-15-one (18): To a stirred mixture of oxalyl chloride (343 mg, 2.71 mmol) in anhydrous dichloromethane (5.7 ml) under nitrogen was added at -60°C (a) a solution of dimethyl sulfoxide (440 mg, 5.63 mmol) in dichloromethane (0.9 ml), (b) after 2 min a solution of **16** (640 mg, 2.32 mmol) in anhydrous dichloromethane (1.5 ml), and (c) after 15 min anhydrous triethylamine (1.6 ml, 11.3 mmol). After further 5 min at -60°C the mixture was allowed to warm up. The mixture was hydrolyzed with water (11 ml), the layers were seperated, the aqueous layer was extracted with dichloromethane

41.80, 52.42, 54.13 (C_{quart}), 108.11 (C_{sek}), 155.23 (C_{quart}); MS m/z 272 (M^+, 6), 71 (100). Anal. calcd for $C_{20}H_{32}$: C, 88.16; H, 11.84. Found: C, 88.22; H, 11.83.

8,8,13,13-Tetramethyltetraspiro[2.0.3.1.3.1.3.0]heptadecane (11): To freshly prepared zinc-silver couple[12] (1.0 g) just covered with anhydrous ether was added under nitrogen with stirring first diiodomethane (777 mg, 2.90 mmol) and then a solution of **21** (35 mg, 0.13 mmol) in anhydrous ether (1.5 ml). The mixture was heated to reflux (bath temperature 50°C) and the reaction progress monitored by glpc [1.8 m x 1/4" all glass system, 15% OV 210 on Chromosorb W AW/DMCS 60/80 mesh, 220°C; rel. retention times: 1.00 (**21**), 1.43 (**11**)]. After 3.5 h, more diiodomethane (777 mg, 2.90 mmol) was added and the heating continued until glpc analysis indicated that the reaction was complete (5 h). The mixture was diluted with ether (5 ml) and the liquid phase decanted and carefully hydrolyzed with saturated ammonium chloride (3 ml). The organic layer was washed with saturated sodium thiosulfate (3 ml), dried over molecular sieves 3 Å and concentrated on a rotary evaporator (bath temperature 20°C/20 torr) to give 35 mg of a yellow solid. Chromatography on silica gel (0.05-0.20 mm) in pentane [column 15 x 1.5 cm; R_f = 0.59 (**11**)] yielded 23 mg (62%) of pure **11** as colourless solid (mp 141-158°C). ^{1}H NMR (200 MHz, $CDCl_3$, $CHCl_3$ int) 0.58 (s, 4H), 0.70 (s, 6H), 1.23-2.38 (m, 18H), 1.47 (s, 6H);); ^{13}C NMR (50.3 MHz, $CDCl_3$, $CDCl_3$ int) 2.38, 10.97, 15.62, 16.31 (C_{sek}), 21.31, 23.78 (C_{prim}), 24.98 (C_{sek}), 25.54 (C_{quart}), 26.31, 26.83, 30.24 (C_{sek}), 41.22, 49.47, 52.65 (C_{quart}); MS m/z 230 (M^+-56, 90), 123 (100).

[1-^{13}C]$_{e,a}$-8,8,13,13-Tetramethyltetraspiro[2.0.3.1.3.1.3.0]heptadecane [1-^{13}C]$_{e,a}$-11): To freshly prepared zinc-silver couple (1.0 g) just covered with anhydrous ether was added under nitrogen with stirring ^{13}C-diiodomethane (431 mg, 1.60 mmol, 90% ^{13}C). The reaction was started by short heating until more ^{13}C-diiodomethane (665 mg, 2.27 mmol) was added at such a rate as to maintain gentle reflux. A solution of **21** (19 mg, 0.07 mmol) in a minimum amount of ether was added and heating continued until glpc analysis indicated that the reaction was nearly complete (1.5 h). Work up and purification as described for **11** yielded 13 mg (75%) of pure [1-^{13}C]$_{e,a}$-**11** as colourless solid. ^{13}C NMR (125.7 MHz, $CDCl_3$, $CDCl_3$ int) 2.38, 10.96; ^{13}C NMR (125.7 MHz, $C_6D_5NO_2$, $C_6D_5NO_2$ int) 2.39, 10.98.

3,3,5,5-Tetramethyl-dispiro[bicyclo[4.3.0]non-1(6)-en-2,1′:4,1′′-biscyclobutane] (22): To a solution of **11** (13 mg, 0.045 mmol) in hexane (0.5 ml) and glacial acetic acid (3.0 ml) was added platinium dioxide (200 mg) and the mixture hydrogenated at 45-50°C and 1.1 atm hydrogen pressure in a shaking gear until capillary glpc [25 m x 0.25 mm i.d. fused silica capillary column coated with 0.25 µm OV 1701, 230°C, 2 ml H_2/min; rel. retention times: 1.00 (**22**), 2.17 (**11**)] indicated that the reaction was complete (4.5 h). Work up as described for **16** yielded 9 mg (77%) of pure **22** as colourless oil. ^{1}H NMR (200 MHz, $CDCl_3$, $CHCl_3$ int) 0.80-2.70 (m, 18H), 0.97 (br s, 6H), 1.03 (s, 3H), 1.23 (s, 3H). ^{13}C NMR (50.3 MHz, 60°C, $CDCl_3$, $CDCl_3$ int) 15.16, 16.64 (C_{sek}), 21.84 (C_{prim}), 24.06(C_{sek}), 25.62 (C_{prim}), 28.97, 29.71, 32.22, 33.62 (C_{sek}), 37.84, 40.63, 48.19, 51.05, 137.62, 137.84 (C_{quart}); MS m/z 258 (M^+, 2), 123 (100); HRMS m/z (M^+) calcd 258.23476, obsd 258.23474.

Kinetic measurements: The ^{13}C NMR spectra for the kinetic measurements were recorded on a Varian VXR 500 spectrometer equipped with a variable temperature probe. The temperatures were measured with a temperature sensor consisting of a 1.8 mm diameter high precision PT 100 resistor (1/5 DIN; accuracy

(11 ml), the combined organic layers were washed with saturated sodium chloride (22 ml), dried over molecular sieves 3 Å, and the solvent was evaporated on a rotary evaporator (bath temperature 20°C/20 torr). The yellow, vile smelling residue (626 mg) was chromatographed on silica gel (0.05-0.20 mm) in pentane/ether [95:5, column 29 x 3 cm; Rf = 0.63 (**18**), 0.58 (**16**)] to yield 496 mg (78%) of pure **18** as colourless solid (mp 120-127°C). IR (KBr) C=O 1685 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$, $CHCl_3$ int) 1.01 (s, 12H), 1.59-1.90 (m, 6H), 2.08-2.30 (m, 8H), 2.36-2.52 (m, 4H); ^{13}C NMR (20 MHz, $CDCl_3$, $CDCl_3$ int) 15.04, 16.57 (C_{sek}), 22.65 (C_{prim}), 25.34, 27.85 (C_{sek}), 42.72, 50.93, 59.38, 214.46 (C_{quart}); MS m/z 274 (M^+, 14), 122 (100); HRMS m/z (M^+) calcd 274.22967, obsd 274.22967.

5,5,10,10,15-Pentamethyltrispiro[3.1.3.1.3.1]pentadecan-15-ol (19): To a solution of **18** (496 mg, 1.81 mmol) in anhydrous ether (8.0 ml) was added at room temperature under nitrogen with stirring a 1.6 M solution of methyllithium in ether (2.0 ml, 3.2 mmol) causing a slightly exothermic effect. Tlc [pentane/ether 95:5; R_f = 0.41 (**18**), 0.25 (**19**)] and glpc analysis [1.8 m x 1/4" all glass system, 15% OV 210 on Chromosorb W AW/DMCS 60/80 mesh, 220°C; rel. retention times: 1.00 (**18**), 1.40 (**19**)] indicated that the reaction was complete. The mixture was carefully hydrolyzed with water, the organic layer washed with saturated ammonium chloride, dried over molecular sieves 3 Å and concentrated on a rotary evaporator (bath temperature 20°C/20 torr) to give 502 mg (96%) of pure **19** as colourless solid (mp 163-165°C). IR (KBr) O-H 3620 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$, $CHCl_3$ int) 0.94 (s, 6H), 1.46 (s, 6H), 1.50-2.52 (m, 19H), 1.88 (s, 3H); ^{13}C NMR (50.3 MHz, C_6D_6, C_6D_6 int) 15.96, 16.83, 22.25, 24.40, 25.24, 25.81, 26.05, 26.17, 27.89, 41.09, 52.05, 52.11, 79.43; MS m/z 232 (M^+-56, 44), 43 (100). Anal. calcd for $C_{20}H_{34}O$: C, 82.69; H, 11.80. Found: C, 82.62; H, 11.74.

2,2,4,4,6-Pentamethyl-dispiro[bicyclo[4.3.0]non-1(9)-ene-3,1´:5,1´´-biscyclobutane] (20) and 5,5,-10,10-Tetramethyl-15-methylenetrispiro[3.1.3.1.3.1]pentadecane (21): To a stirred mixture of **19** (374 mg, 1.29 mmol) in hexamethylphosphorous triamide (7.0 ml) under nitrogen was added at room temperature with stirring phosphorous oxychloride (789 mg, 5.15 mmol). A white precipitate was formed. After 30 min at room temperature and 1 h at 50°C, anhydrous pyridine (510 mg, 5.18 mmol) was added whereby the precipitate dissolved. After 1 h at 80°C and 5 h at 100°C tlc [pentane/ether 95:5; R_f = 0.65 (**20**, **21**), 0.20 (**19**)] indicated that the reaction was complete. The crude reaction mixture was chromatographed on silica gel (0.05-0.20 mm) in pentane [column 38 x 2 cm; R_f = 0.63 (**20**, **21**)] to give 350 mg (99%) of a 1:1 mixture of **20** and **21**. Seperation was achieved by twofold chromatography on silica gel impregnated with silver nitrate (20%, w/w) in pentane/dichloromethane [95:5, columns 62 x 2 and 43 x 1.5 cm; R_f = 0.09 (**20**), 0.04 (**21**)] and yielded 106 mg (31%) of pure **20** (mp 92-100°C) and 120 mg (34%) of pure **21** (mp 50-62°C) as colourless solids. **20:** ^1H NMR (200 MHz, $CDCl_3$, $CHCl_3$ int) 1.06 (s, 3H), 1.17 (s, 6H), 1.22 (s, 3H), 1.27 (s, 3H), 1.40-2.50 (m, 16H), 5.36 (m, 1H); ^{13}C NMR (50.3 MHz, $CDCl_3$, $CDCl_3$ int) 16.13, 22.86, 23.00, 24.90 (coincidence of two lines), 25.83, 25.95, 27.14, 28.07, 28.62, 29.40, 39.26, 40.33, 42.23, 52.35, 52.72, 121.38; the quaternary carbon atom of the double bond could not be detected; MS m/z 272 (M^+, 17), 229 (100). Anal. calcd for $C_{20}H_{32}$: C, 88.16; H, 11.84. Found: C, 88.12; H, 11.81. **21:** ^1H NMR (200 MHz, $CDCl_3$, $CHCl_3$ int) 0.52 (s, 6H), 1.48 (s, 6H), 1.58-1.82 (m, 6H), 1.90-2.46 (m, 12H), 5.03 (s, 2H); ^{13}C NMR (20 MHz, $CDCl_3$, $CDCl_3$ int) 15.44, 16.96 (C_{sek}), 21.34, 23.16 (C_{prim}), 26.25, 26.60, 28.65, 30.85 (C_{sek}),

± 0.005°C from 0 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 the equilibrations, the temperatures were precise within ± 0.4°C. Precision 5 mm o.d. NMR tubes were filled with solutions of 1.8 mg for the equilibration at 58.0°C, and 3.6 mg for the equilibrations at 65.0 and 70.0°C, respectively, of [1-^{13}C]$_{e,a}$-**11** in 560 µl of nitrobenzene-d_5 and the increase in concentration of [1-^{13}C]$_a$-**11** followed by ^{13}C NMR [125.7 MHz, aquisition time 1.501 sec, pulse with 25°, number of transients 192 (58.0°C), 116 (65.0°C), 76 (70.0°C)]. The spectra were taken at appropriate times and the initial (I_o) and actual concentrations (I) determined by measuring the intensities of the corresponding resonance lines. To ensure complete equilibration, the solutions of [1-^{13}C]$_{e,a}$-**11** were finally heated for 24 h to 100°C until the equilibration concentration (I_e) was determined. The equilibrium constant amounted to K = 1.000 and therefore no corrections had to be made.

Calculations: The least-squares approximations of $\ln[(I_o-I_e)/(I-I_e)] = [k([1-^{13}C]_e\text{-}\mathbf{11}) + k([1-^{13}C]_a\text{-}\mathbf{11})]\cdot t$ (Figure 1) and the adjustment of the rate data to the Eyring equation (Figure 2) were done with the computer program ACTPAR.

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