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The Thermal Transformations of Bicyclopropylidene and Methylenespiropentane Revisited

Heiko Schill,[a] Sergei I. Kozhushkov,[a] Robin Walsh,*[b] and Armin de Meijere*[a]

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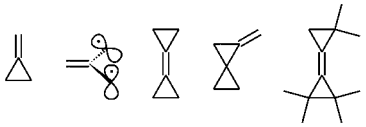
The overall and the individual rate constants of the unimolecular thermal isomerization of methylenespiropentane (**4**) to 1,2- and 1,3-dimethylenecyclobutanes (**7** and **8**) have been determined to be $\lg(k_{-4}/s^{-1}) = (13.78 \pm 0.06) - (49.7 \pm 0.2)$ kcal mol^{-1}/RT·ln 10, $\lg(k_7/s^{-1}) = (13.03 \pm 0.19) - (48.0 \pm 0.6)$ kcal mol^{-1}/RT·ln 10 and $\lg(k_8/s^{-1}) = (14.15 \pm 0.19) - (52.4 \pm 0.5)$ kcal mol^{-1}/RT·ln 10, respectively. The activation energies are significantly lower than that for the rearrangement of the parent spiropentane.

Introduction

Methylenecyclopropane (**1**) and its derivatives with their strain energy of ca. 42 kcal mol^{-1}[1] have demonstrated a unique reactivity and consequently enjoyed an ever increasing application as building blocks in organic synthesis.[2] Among their reactions, the degenerate thermal isomerization via a trimethylenemethane diradical intermediate of type **2** is of special interest.[3] This isomerization has been studied extensively from a theoretical[4] and a preparative[3] point of view for methylenecyclopropane (**1**) itself as well as for substituted methylenecyclopropanes. Bicyclopropylidene (**3**),[5] which is an even more highly strained cyclopropane-annelated symmetrical derivative of **1**, has also attracted considerable interest as a versatile multifunctional six-carbon building block.[6] In contrast to that of methylenecyclopropane (**1**), the thermal reorganization of **3** is not degenerate and leads to an isomer of **3**, i.e. methylenespiropentane (**4**).

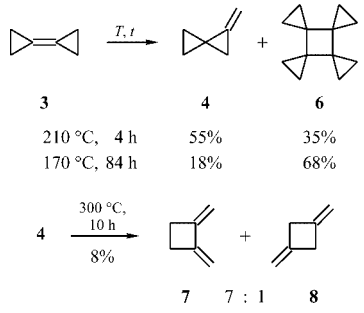


1 **2** **3** **4** **5**

Crandall et al., who were the first to shed some light on the family of bicyclopropylidene and its derivatives, heated 2,2,2′,2′,3,3-hexamethylbicyclopropylidene (**5**) in a flow pyrolysis system to 400 °C and obtained a 10:1 mixture of two isomeric hexamethylmethylenespiropentanes formed through trimethylenemethane diradical intermediates.[7a]

Analogous transformations have been reported for isomeric tetramethylbicyclopropylidenes,[7b,7c] dichlorotetramethylbicyclopropylidenes[7d] and 1,1-dideuteriobicyclopropylidene.[7e] The mechanistic, kinetic and preparative aspects of these reactions have been reviewed.[6a,8] For the unsubstituted hydrocarbon **3**, the kinetic parameters do not differ much from those for the parent methylenecyclopropane (**1**).[9]

Methylenespiropentane (**4**), formed as the main product from **3** at 210 °C, does not persist at more elevated temperatures. At 300 °C and above, the same trimethylenemethane-type radical formed from **4** and from **3**, undergoes further rearrangement leading to mixtures of 1,2- and 1,3-dimethylenecyclobutane (**7** and **8**) (Scheme 1). This rearrangement was first discovered in 1968;[10] however, detailed kinetic data for this process have never been determined.



Scheme 1. Known thermal transformations of bicyclopropylidene (**3**) and methylenespiropentane (**4**).

Another known thermally induced transformation of bicyclopropylidene (**3**) is its dimerization to form the so-called [4]rotane (**6**).[11] This reaction is known to proceed either upon heating of compound **3** neat or in solution in a

[a] Institut für Organische und Biomolekulare Chemie der Georg-August-Universität, Göttingen, Tammannstrasse 2, 37077 Göttingen, Germany
Fax: +49-551-399475
E-mail: armin.demeijere@chemie.uni-goettingen.de
[b] Department of Chemistry, University of Reading, Whiteknights, P. O. Box 224, Reading RG6 6AD, Great Britain
E-mail: r.walsh@reading.ac.uk

closed vessel, and it competes with the isomerization of **3** to **4**. The relative amounts of **4** and **6** depend on the reaction conditions employed.[6a] The mechanism of this dimerization process is still a matter of debate.

Therefore, in spite of more than 35 years of history, there are still several open questions considering the thermal reorganizations of bicyclopropylidene (**3**) and its isomer methylenespiropentane (**4**). Here we present a detailed kinetic study on the rearrangement of **4** to the dimethylenecyclobutanes **7** and **8**.

Results and Discussion

For the detailed study of the kinetics of the isomerization of methylenespiropentane (**4**), mixtures of **4** and *n*-pentane as an internal standard (ca. 1.5% each) with nitrogen (97%) were pyrolyzed in the gas phase at six different temperatures in the range of 330–380 °C using a static reactor setup. The results of the single runs are compiled in Table 2 (see Exp. Sect.). A small amount of allene (1.5% of the total products at 330 °C increasing to 2.7% at 380 °C) has been found in the pyrolysate, potentially arising from fragmentation of dimethylenecyclobutanes **7** or **8** or any precursors to them. Since the total amount is very small, no efforts have been made to take this into account during rate-constant calculations. To rule out a radical chain or surface-catalyzed transformation, the reaction was also performed in the presence of a large excess of propene as a radical scavenger and employing different surface/volume ratios of the reactor. Experiments conducted at varying pressures showed that the reaction in the applied range of p_i = 15–30 Torr really follows first-order kinetics, and is not affected by "fall-off" phenomena which would set in at significantly higher pressures. The results of these tests are presented in Table 3 (see Exp. Sect.). For the data shown in Table 2, good linear first-order plots {$\lg[c(\mathbf{4})/c_0(\mathbf{4})]$ vs. time} were found at all temperatures, and the individual rate constants k_{-4} were obtained by least-mean-squares fitting (Table 1). From these values the Arrhenius parameters presented in Equation (1) were obtained (Figure 1).

$$\lg(k_{-4}/s^{-1}) = (13.78 \pm 0.06) - (49.7 \pm 0.2)\ \text{kcal mol}^{-1}/RT\cdot\ln 10 \quad (1)$$

Table 1. Overall rate constant k_{-4} for the disappearance of **4** and individual rate constants k_7 and k_8 for the formation of 1,2-dimethylenecyclobutane (**7**) and the 1,3-isomer **8**.

T [°C]	330.5	340.5	349.8	359.2	369.5	379.2
$10^4\ k_{-4}/s^{-1}$	0.610	1.22	2.25	4.00	7.69	12.8
$10^4\ k_7/s^{-1}$	0.462	0.917	1.66	2.88	5.53	9.02
$10^4\ k_8/s^{-1}$	0.148	0.303	0.593	1.12	2.16	3.78

Using the mean value of the ratio $r = c(\mathbf{7})/c(\mathbf{8})$ for a given temperature, the rate constants k_{-4} could be separated into the individual rate constants k_7 and k_8 according to Equations (2) and (3). The separated values are compiled in Table 1.

The plots of these individual rate constants also displayed linear first-order dependencies for both isomers.

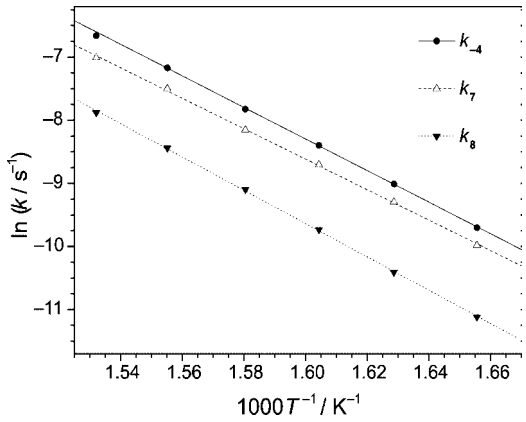


Figure 1. Arrhenius plots of the overall rate constants k_{-4} and the individual rate constants k_7 and k_8 for the rearrangement of methylenespiropentane (**4**) to dimethylenecyclobutanes **7** and **8**.

$$k_7 = k_{-4} \times r/(1 + r) \quad (2)$$

$$k_8 = k_{-4} - k_7 \quad (3)$$

Thus, individual Arrhenius parameters for the formation of **7** and **8** [Equations (4) and (5)] could also be determined.

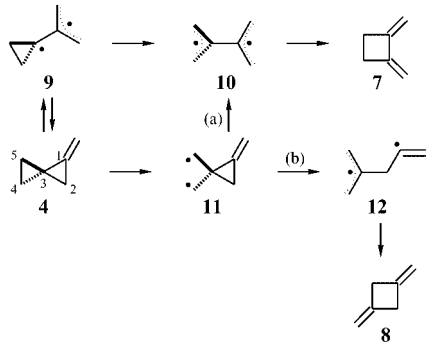
$$\lg(k_7/s^{-1}) = (13.03 \pm 0.19) - (48.0 \pm 0.6)\ \text{kcal mol}^{-1}/RT\cdot\ln 10 \quad (4)$$

$$\lg(k_8/s^{-1}) = (14.15 \pm 0.19) - (52.4 \pm 0.5)\ \text{kcal mol}^{-1}/RT\cdot\ln 10 \quad (5)$$

Although the mechanism of the rearrangement of methylenespiropentane (**4**) to the dimethylenecyclobutanes **7** and **8** is not known, it seems likely that the reaction proceeds via diradical intermediates.[8] Formally, methylenespiropentane (**4**) can be regarded as a superposition of methylenecyclopropane (**1**) and spiropentane. The thermal rearrangements of both of the latter hydrocarbons have been studied in detail before.[8] The spiropentane → methylenecyclobutane rearrangement is conceived to proceed through a diradical formed by initial homolytic cleavage of the C(1)–C(2) bond.[12a] This mechanism was later supported by ab initio calculations.[12b] The activation energy for this process has been determined to be 57.6 kcal mol^{-1}.[13] In the case of methylenecyclopropane (**1**), the accepted mechanism starts with the homolytic cleavage of the distal bond C(2)–C(3) leading to the trimethylenemethane (TMM) intermediate **2**. The activation energies for the rearrangement of **1** and for methyl derivatives thereof range from 36 to 42 kcal mol^{-1}.[14]

The much lower measured activation energy for the rearrangement of methylenecyclopropane (**1**) compared with that of spiropentane gives a strong hint that in the methylenespiropentane thermal reorganization, the distal (with respect to the methylene group) bond C(2)–C(3) must be the weakest and should break first to give the diradical intermediate **9** (Scheme 2). This should then be followed by cyclopropyl ring opening in **9** to give the biallyl diradical **10** which forms 1,2-dimethylenecyclobutane (**7**) by allylic recombination. There is no obvious route to **8** via **9** and **10**. If, however, the rearrangement of **4** imitates that of spiropentane, then the C(4)–C(5) bond would open to give dirad-

ical **11**. This species then has two possibilities. If C(2)–C(3) subsequently breaks [pathway (a)], then **10** is formed which will lead to **7**. If, however, C(1)–C(3) breaks [pathway (b)], then diradical **12** is produced, and this will lead to **8** by allyl/vinyl radical recombination (Scheme 2).

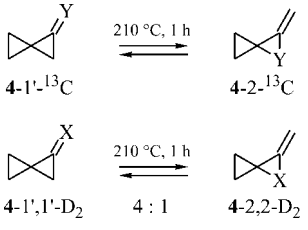


Scheme 2. Pathways for the rearrangement of methylenespiropentane (**4**) to dimethylenecyclobutanes **7** and **8**.

Compared to **11**, both diradicals **9** and **10** should be energetically favored since they benefit from allylic stabilization. Energetically, formation of **11** should not be able to compete with formation of **9**. However, formation of both **7** and **8** suggests that both pathways must be taken. The resolution of this dilemma is probably the difficulty of the cyclopropyl ring-opening step in the **9** → **10** rearrangement. Although the barrier for this step is not known, some idea of its magnitude may be deduced from that for the cyclopropyl radical ring opening for which both experiment[15] and theory[16] give values of 22 ± 2 kcal/mol. Use of this figure allows one to make an approximate comparison of the energetics of each pathway. Formation of **9** leads to the release of ca. 50.5 kcal/mol of strain (41.7 kcal/mol for methylenecyclopropane[17] and 8.8 kcal/mol for the "spiro increment"[17]) whereas formation of **11** releases only ca. 36.9 kcal/mol of strain (28.1 kcal/mol for cyclopropane[17] and 8.8 kcal/mol for the "spiro increment"[17]). The energetic advantage of forming **9** rather than **11** (13.6 kcal/mol) is less than the disadvantage of the cyclopropyl ring-opening barrier. This estimate neglects the barriers to ring closure of **11**. However, it is known that the cyclopropylmethyl radical ring-opening reaction (to give the but-1-en-4-yl radical) is an extremely facile process which therefore must have a low reclosure barrier.[18] Since the two pathways, (a) and (b), for reaction of **11** are both exothermic, this can explain why the breaking of the apparently stronger C(1)–C(3) bond in **11** competes with breaking of the weaker C(2)–C(3) bond. Thus, these considerations can account for the formation of both **7** and **8** in the thermal rearrangement of **4**. Unfortunately, since the ratio of the rates of pathways (a) and (b) are not known, the proportions of **7** being formed via **9** and **11** cannot be evaluated. Moreover, it is not possible to distinguish these two routes by labeling experiments, because the only difference between them is the order in which the very same bonds break.[8,10] The observed activation energy of 48.0 kcal/mol for the formation of **7** is more in line with the pathway via **9**, since the route via **11** should require roughly the same activation energy (57.6 kcal/mol) as that for the thermal isomerization of spiropentane.[8,13] The lower value of lg A = 13.03 for this pathway is much closer to that for 2-methylmethylenecyclopropane (14.26)[14b] than to those for spiropentane (15.86)[13] and cyclopropane (15.17).[19] The increased activation energy for the formation of **7** compared with that for the rearrangement of 2-methylmethylenecyclopropane (40.4 kcal/mol)[14b] must be accounted for by an extra barrier for the cyclopropyl radical opening **9** → **10** as discussed above. The Arrhenius parameters for the formation of **8** (14.15 and 52.4 kcal/mol) are low by comparison with those of spiropentane to fit a pathway by which **11** would be formed directly from **4**. While there may be more uncertainty in the Arrhenius parameters for the minor product compared with those for the major product, comparisons with spiropentane are not strictly valid because of the added complication of the relative contributions of pathways (a) and (b), which will effect the relative yields of **7** and **8**.

In the single reported experiment by Dolbier,[10] a sample of **4** heated at 300 °C for 10 h furnished a 7:1 mixture of **7** and **8** in 8% yield. While the overall yield is consistent with that expected by extrapolation of our results (temperature range 330–370 °C) the predicted ratio (ca 3.5:1) of **7**/**8** is not. We are not able to account for this difference but we note that Dolbier's experimental conditions (sealed tube pyrolysis) were very different from ours. Although the ratio decreases slightly with increasing temperature, it shows no time dependence (although there is some experimental scatter in values). The ratio appears to be determined by kinetic, and not thermodynamic considerations. It should also be noted that the small amounts of allene detected in our experiments, mean that decomposition of either **7** or **8** (most probably **7**) is rather slight and cannot affect the true ratio of **7**/**8** significantly. Reverse dimerization of allene cannot occur at the low pressures of these gas-phase experiments.

It is an important consequence of these arguments that, in the mechanism of Scheme 2, diradical **9** is effectively in equilibrium with **4** under pyrolysis conditions. To verify this, we have carried out isotopic scrambling experiments at temperatures well below those of pyrolysis (Scheme 3).



Scheme 3. Scrambling of ^{13}C and D_2 labels in 1′-labeled methylenespiropentanes (Y = $^{13}CH_2$, X = CD_2).

A significant degree of ^{13}C-atom scrambling into the 2-position was observed, when a sample of 1′-^{13}C-labeled methylenespiropentane **4**-1′-^{13}C was heated at 210 °C for 1 h in a sealed tube. Since quantification of this scrambling

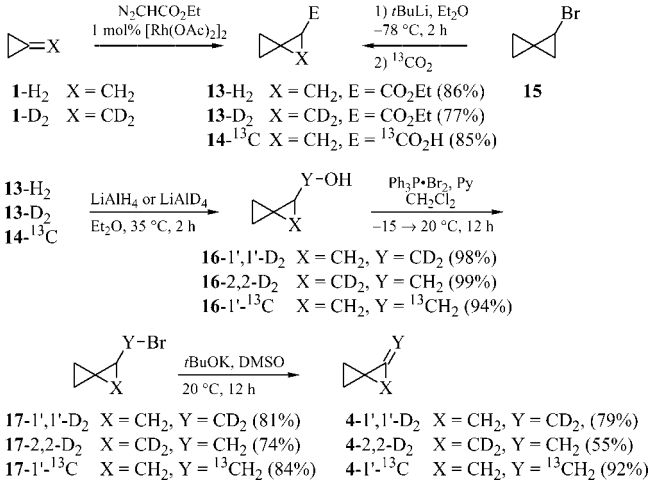
is difficult on the basis of ^{13}C-signal intensities – due to the different relaxation times of vinylic and cyclopropylic carbon atoms – the (1′,1′-dideuteriomethylene)spiropentane (**4**-1′,1′-D_2) was also prepared. After 1 h at 210 °C, a mixture of **4**-1′,1′-D_2/**4**-2,2-D_2 (ratio 4:1) was obtained as quantified on the basis of ^1H-NMR spectra of the mixture and of an authentic sample of **4**-2,2-D_2.

Conclusions

The kinetic data of the thermal rearrangement of methylenespiropentane (**4**) leading to 1,2-dimethylenecyclobutane (**7**) are consistent with an allylic bond rupture in **4** to give the cyclopropyl-allyl diradical **9** and subsequent formation of the 2,2′-biallyl diradical **10**. Formation of 1,3-dimethylenecyclobutane (**8**) seems to demand rupture of the C(4)–C(5) bond in **4** leading to the non-allylic diradical **11** and then to an allyl/vinyl diradical **12**. Some **7** could also be formed along this route.

Experimental Section

General: ^1H- and ^{13}C-NMR spectra: at 250 (^1H), and 62.9 MHz [^{13}C, additional DEPT (Distortionless Enhancement by Polarization Transfer)] with a Bruker AM 250 instrument in $CDCl_3$ solution, $CHCl_3$/$CDCl_3$ as internal reference. Anhydrous DMSO and CH_2Cl_2 were distilled from CaH_2 and anhydrous diethyl ether and THF were obtained by distillation from sodium benzophenone ketyl. Organic solutions were dried with $MgSO_4$. All hydrocarbons were isolated or purified by preparative gas chromatography (20% SE 30 on Chromosorb W-AW-DMCS, 1000 mm × 8.2 mm column, 70 °C). Methylenespiropentane (**4**) was prepared according to a published procedure.[9] The labeled methylenespiropentanes **4**-1′,1′-D_2, **4**-2,2-D_2, and **4**-1′-^{13}C were prepared from methylenecyclopropane (**1**-H_2),[20] (dideuteriomethylene)cyclopropane (**1**-D_2)[14a] and bromospiropentane (**15**),[21] respectively, as shown in Scheme 4 [for the preparation of ethyl spiropentanecarboxylate (**13**-H_2) see ref.[5b]]. All other chemicals were used as commercially available. All preparations were carried out under argon.



Scheme 4. Preparation of ^{13}C- and D_2-labeled methylenespiropentanes (Y = $^{13}CH_2$; X = CD_2).

Ethyl 2,2-Dideuteriospiropentanecarboxylate (13-D_2): To a solution of (dideuteriomethylene)cyclopropane (**1**-D_2) (3.67 g, 65.4 mmol) and dirhodium tetraacetate (265 mg, 579 μmol) in anhydrous dichloromethane (50 mL) was added ethyl diazoacetate (6.85 g, 6.31 mL, 60.0 mmol) at 0 °C within 12 h. The reaction mixture was filtered through a pad of silica gel and, after concentration under reduced pressure at 0 °C, the product was isolated by distillation to give 6.56 g (77%) of **13**-D_2, b.p. 68–71 °C (21 mbar). ^1H NMR: δ = 0.79–0.93 (m, 4 H, 2 CH_2), 1.20 (t, J = 7.0 Hz, 3 H, CH_3), 1.88 (s, 1 H, CH), 4.0–4.14 (m ABX_3, 2 H, CH_2O) ppm. ^{13}C NMR: δ = 14.24 (CH_3), 4.99, 6.74 (CH_2), 20.16 (CH), 18.25, 173.81 (C), 14.07 (quint, J = 23 Hz, CD_2) ppm.

Spiropentane[^{13}C]carboxylic Acid (14-^{13}C): *tert*-Butyllithium (89.2 mmol, 59.5 mL of a 1.50 M solution in pentane) was added to a solution of bromospiropentane (**15**) (6.56 g, 44.6 mmol) in anhydrous Et_2O (100 mL) at –78 °C within 1 h. After additional stirring at –78 °C for 1 h, a stream of $^{13}CO_2$ diluted with Ar was slowly passed through at –78 °C, and after this the mixture was warmed to 20 °C and extracted with ice-cold water (50 mL). The aqueous phase was washed with Et_2O (50 mL), acidified to pH = 2 with 12 N HCl solution at 5 °C and extracted with Et_2O (4 × 30 mL). The combined organic phases were dried and concentrated under reduced pressure to give 4.30 g (85%) of the acid **14**-^{13}C as an oil, which was used without further purification. ^1H NMR: δ = 0.86–1.00 (m, 4 H, 2 CH_2), 1.43 (dd, J = 4.3, 7.5 Hz, 1 H, CH_2), 1.53 (q, J = 4.3 Hz, 1 H, CH_2), 1.94 (dd, J = 4.3, 7.5 Hz, 1 H, CH), 8.15 (s, 1 H, OH) ppm. ^{13}C NMR: δ = 5.3, 6.7 (CH_2), 15.9 (d, J = 1.5 Hz, CH_2), 19.4 (d, J = 2.1 Hz, C), 20.3 (d, J = 73.5 Hz, CH), 180.5 (^{13}C) ppm.

Preparation of Spiropentylmethanols 16. General Procedure (GP) 1: A solution of ethyl spiropentylcarboxylate (**13**)[5b] or spiropentylcarboxylic acid (**14**) (40 mmol) in Et_2O (15 mL) was added dropwise at ambient temperature to a suspension of $LiAlH_4$ or $LiAlD_4$ (20 mmol for **13**-H_2 and **13**-D_2, respectively, or 30 mmol for **14**-^{13}C) in Et_2O (50 mL). After 2 h under reflux, quenching with satd. Na_2SO_4 solution and filtration, the precipitate was additionally extracted with Et_2O in a Soxhlet apparatus overnight. The combined ethereal solutions were dried and concentrated under reduced pressure. The residue was pure enough to be used without further purification.

1,1-Dideuterio-1-spiropentylmethanol (16-1′,1′-D_2): From the ester **13**-H_2 (5.53 g, 39.5 mmol) and $LiAlD_4$ (830 mg, 19.8 mmol), the alcohol **16**-1′,1′-D_2 (3.87 g, 98%) was obtained according to GP1. ^1H NMR: δ = 0.49 (t, J = 4.3 Hz, 1 H, CH_2), 0.54–0.69 (m, 4 H, 2 CH_2), 0.85 (dd, J = 4.3, 7.5 Hz, 1 H, CH_2), 1.26 (dd, J = 4.3, 7.5 Hz, 1 H, CH), 3.73 (s, 1 H, OH) ppm. ^{13}C NMR: δ = 3.0, 5.0, 10.4 (CH_2), 19.4 (CH), 13.2 (C), 65.0 (quint, J = 21.6 Hz, CD_2) ppm.

(2,2-Dideuteriospiropentyl)methanol (16-2,2-D_2): From the ester **13**-D_2 (6.56 g, 46.2 mmol) and $LiAlH_4$ (877 mg, 23.1 mmol), the alcohol **16**-2,2-D_2 (4.58 g, 99%) was obtained according to GP1. ^1H NMR: δ = 0.61–0.73 (m, 4 H, 2 CH_2), 1.34 (t, J = 7.0 Hz, 1 H, CH), 2.81 (s, 1 H, OH), 3.48 (dd, J = 7.0, 13.8 Hz, 1 H, OCH_2), 3.62 (dd, J = 7.0, 13.8 Hz, 1 H, OCH_2) ppm. ^{13}C NMR: δ = 3.1, 5.1, 66.0 (CH_2), 9.9 (quint, J = 25.9 Hz, CD_2), 19.1 (CH), 13.1 (C) ppm.

Spiropentyl[^{13}C]methanol (16-1′-^{13}C): From the acid **14**-^{13}C (4.30 g, 38.0 mmol) and $LiAlH_4$ (1.08 g, 28.5 mmol), the alcohol **16**-1′-^{13}C (3.53 g, 94%) was obtained according to GP1. ^1H NMR: δ = 0.58 (dd, J = 4.5, 9.8 Hz, 1 H, CH_2), 0.63–0.78 (m, 4 H, 2 CH_2), 0.94 (dt, J = 3.5, 7.0 Hz, 1 H, CH_2), 1.37 (ddd, J = 4.5, 7.0, 14.5 Hz, 1 H, CH), 3.47 (ddd, J = 6.8, 11.2, 141.8 Hz, 1 H, O$^{13}CH_2$), 3.56

(ddd, J = 6.8, 11.2, 141.8 Hz, 1 H, O^{13}CH$_2$), 4.68 (s, 1 H, OH) ppm. ^{13}C NMR: δ = 3.2 (d, J = 2.5 Hz, CH$_2$), 5.2, 10.6 (CH$_2$), 19.4 (d, J = 47.4 Hz, CH), 13.2 (C), 66.2 (^{13}CH$_2$) ppm.

Preparation of Spiropentylmethyl Bromides 17. General Procedure (GP) 2: To a solution of triphenylphosphane (1.05 equiv.) in anhydrous dichloromethane (50 mL), bromine (1.05 equiv.) was added at –30 to –15 °C over a period of 10 min. After an additional 15 min of stirring, a mixture of alcohol (35 mmol) and anhydrous pyridine (1 equiv.) was added dropwise at –15 °C over a period of 15 min. The mixture was stirred at 20 °C for an additional 12 h, and then all the volatile material was "bulb-to-bulb"-distilled into a trap cooled to –78 °C, at first under water-aspirator vacuum and 30 °C oil-bath temperature, and then under further reduced pressure (0.1 Torr) with an oil bath (100 °C). The receiver flask was warmed up to 20 °C, and the solvent was removed by distillation at atmospheric pressure using a 30-cm Vigreux column. The residue was distilled under reduced pressure.

(Bromodideuteriomethyl)spiropentane (17-1′,1′-D$_2$): From the alcohol **16**-1′,1′-D$_2$ (3.87 g, 38.7 mmol), Ph$_3$P (10.65 g, 40.6 mmol), Br$_2$ (6.49 g, 2.09 mL, 40.6 mmol) and pyridine (3.11 g, 3.28 mL), the bromide **17**-1′,1′-D$_2$ (5.10 g, 81%) was obtained according to GP2, b.p. 78–80 °C (99 mbar). ^{1}H NMR: δ = 0.64–0.74 (m, 2 H, CH$_2$), 0.76–0.84 (m, 2 H, CH$_2$), 0.77 (dd, J = 4.5, 7.0 Hz, 1 H, CH$_2$), 1.14 (dd, J = 4.5, 7.5 Hz, 1 H, CH$_2$), 1.61 (dd, J = 7.0, 7.5 Hz, 1 H, CH) ppm. ^{13}C NMR: δ = 2.6, 6.0, 14.7 (CH$_2$), 19.7 (CH), 17.5 (C), 38.0 (quint, J = 23.4 Hz, CD$_2$) ppm.

1-(Bromomethyl)-2,2-dideuteriospiropentane (17-2,2-D$_2$): From the alcohol **16**-2,2-D$_2$ (4.58 g, 45.7 mmol), Ph$_3$P (12.59 g, 48 mmol), Br$_2$ (7.67 g, 2.47 mL, 48 mmol) and pyridine (3.62 g, 3.70 mL), the bromide **17**-2,2-D$_2$ (5.51 g, 74%) was obtained according to GP2, b.p. 75–77 °C (99 mbar). ^{1}H NMR: δ = 0.66–0.71 (m, 1 H, CH$_2$), 0.75–0.84 (m, 2 H, CH$_2$), 0.92–0.98 (m, 1 H, CH$_2$), 1.71 (t, J = 7.0 Hz, 1 H, CH), 3.33 (dd, J = 7.0, 9.8 Hz, 1 H, BrCH$_2$), 3.51 (dd, J = 7.0, 9.8 Hz, 1 H, BrCH$_2$) ppm. ^{13}C NMR: δ = 2.6, 6.0, 39.7 (CH$_2$), 19.8 (CH), 17.4 (C), 14.2 (quint, J = 23.1 Hz, CD$_2$) ppm.

([^{13}C]Bromomethyl)spiropentane (17-1′-^{13}C): From the alcohol **16**-1′-^{13}C (3.53 g, 35.6 mmol), Ph$_3$P (10.05 g, 38.3 mmol), Br$_2$ (6.13 g, 1.97 mL, 38.3 mmol) and pyridine (2.77 g, 2.83 mL), the bromide **17**-1′-^{13}C (4.86 g, 84%) was obtained according to GP2, b.p. 77–78 °C (95 mbar). ^{1}H NMR: δ = 0.66–0.74 (m, 2 H, CH$_2$), 0.78–0.86 (m, 2 H, CH$_2$), 0.93–0.97 (m, 1 H, CH$_2$), 1.16 (quint, J = 3.6 Hz, 1 H, CH$_2$), 1.60–1.65 (m, 1 H, CH), 3.33 (ddd, J = 8.3, 9.8, 153.0 Hz, 1 H, BrCH$_2$), 3.52 (ddd, J = 6.8, 9.8, 153.0 Hz, 1 H, BrCH$_2$) ppm. ^{13}C NMR: δ = 2.7 (d, J = 2.9 Hz, CH$_2$), 6.0, 14.8 (CH$_2$), 17.6 (d, J = 2.6 Hz, C), 20.0 (d, J = 46.9 Hz, CH), 38.7 (^{13}CH$_2$) ppm.

Preparation of Labeled Methylenespiropentanes 4. General Procedure (GP) 3: To a stirred solution of potassium *tert*-butoxide (1.3 equiv.) in anhydrous dimethyl sulfoxide (50 mL), 30 mmol of the respective neat spiropentylmethyl bromide **17** was added over a period of 0.5 h, while the temperature was maintained between 20 and 25 °C. After additional stirring in a closed flask at ambient temperature for 12 h, all the volatile material was "bulb-to-bulb"-distilled into the cold trap under reduced pressure (0.1 Torr) at a maximum temperature of 40 °C inside the flask. The content of the cold trap was warmed up to 20 °C, washed with four 5-mL portions of ice-cold water and transferred into a preweighed vessel containing a couple of granules of molecular sieves (4 Å). The products were of 93–95% purity.

(Dideuteriomethylene)spiropentane (4-1′,1′-D$_2$): From the bromide **17**-1′,1′-D$_2$ (4.89 g, 30 mmol) and *t*BuOK (4.38 g, 39 mmol), **4**-1′,1′-D$_2$ (1.95 g, 79%) was obtained according to GP3. ^{1}H NMR: δ = 1.02–1.19 (m AA′BB′, 4 H, 2 CH$_2$), 1.38 (s, 2 H, CH$_2$) ppm. ^{13}C NMR: δ = 10.0 (CH$_2$), 10.1 (2 CH$_2$), 10.6, 137.2 (C), 97.9 (quint, J = 24.7 Hz, CD$_2$) ppm.

2,2-Dideuterio-1-methylenespiropentane (4-2,2-D$_2$): From the bromide **17**-2,2-D$_2$ (4.89 g, 30 mmol) and *t*BuOK (4.38 g, 39 mmol), **4**-2,2-D$_2$ (1.36 g, 55%) was obtained according to GP3. ^{1}H NMR: δ = 1.02–1.19 (m AA′BB′, 4 H, 2 CH$_2$), 5.15 (s, 1 H, =CH$_2$), 5.29 (s, 1 H, =CH$_2$) ppm. ^{13}C NMR: δ = 10.1 (2 CH$_2$), 98.5 (CH$_2$), 10.5, 137.3 (C), 10.0 (quint, J = 26.2 Hz, CD$_2$) ppm.

([^{13}C]Methylene)spiropentane (4-1′-^{13}C): According to GP3, a mixture (2.17 g) of the labeled methylenespiropentane **4**-1′-^{13}C and *tert*-butyl spiropentyl[^{13}C]methyl ether (72:28) was obtained from the bromide **17**-1′-^{13}C (4.70 g, 29.0 mmol) and *t*BuOK (4.23 g, 37.7 mmol). **4**-1′-^{13}C: 1.20 g, 52% (based on the ^{1}H-NMR spectrum). ^{1}H NMR: δ = 1.02–1.19 (m AA′BB′, 4 H, 2 CH$_2$), 1.38 (dd, J = 2.0, 3.8 Hz 2 H, CH$_2$), 5.15 (ddt, J = 0.5, 2.0, 160.3 Hz, 1 H, =^{13}CH$_2$), 5.29 (d, J = 161.5 Hz, 1 H, =^{13}CH$_2$) ppm. ^{13}C NMR: δ = 10.1 (CH$_2$), 10.2 (2 CH$_2$), 10.6 (C), 98.8 (^{13}CH$_2$), 137.5 (d, J = 98.5 Hz, C) ppm. *tert*-Butyl spiropentyl[^{13}C]methyl ether: 939 mg, 21% (based on the ^{1}H-NMR spectrum). ^{1}H NMR: δ = 0.57–0.78 (m, 4 H, 2 CH$_2$), 1.00–1.11 (m, 3 H, CH$_2$ + CH), 1.27 (s, 9 H, 3 CH$_3$), 3.22 (ddd, J = 7.3, 9.3, 140.0 Hz, 1 H, O^{13}CH$_2$), 3.32 (ddd, J = 6.5, 9.3, 141.5 Hz, 1 H, O^{13}CH$_2$) ppm. ^{13}C NMR: δ = 3.5 (CH$_2$), 5.4 (CH$_2$), 11.2 (CH$_2$), 13.4 (C), 17.4 (d, J = 50.3 Hz, CH), 27.6 (3 CH$_3$), 65.5 (^{13}CH$_2$), 72.3 (C) ppm.

Scrambling of ^{13}C and D$_2$ Labels in 1′-Labeled Methylenespiropentanes 4: A sample of each of the 1′-labeled methylenespiropentane **4** (50–80 mg) was placed in a thick-walled ampoule (volume ca. 1 mL). The ampoule was purged with Ar and sealed before being heated in an oven at 210 °C for 60 min. The contents of the ampoules were analyzed on the basis of their ^{1}H- and ^{13}C-NMR spectra.

Kinetic Measurements of the Rearrangement of Methylenespiropentene (4) in the Gas Phase: The apparatus used was a static conventional grease-free vacuum system made from Pyrex, with Youngs stopcocks. The spherical reaction vessel (volume ca. 250 mL) was placed in a stirred salt ($NaNO_2/KNO_3$ eutectic) bath thermostat controlled by an AEI (GEC) RT3R/2 controller. Temperatures were measured with a calibrated Pt/Pt-13%Rh thermocouple. Pressures $\geq$ 1 Torr were measured with a conventional mercury manometer, pressures $<$ 1 Torr with Pirani G5C-2 and Speedivac B4 (Edwards) instruments. Product-mixture analyses were performed by gas chromatography with a Perkin–Elmer 8310 chromatograph (4 m $\times$ 2.3 mm, 15% MS550 on Chromosorb 60/80W, 35 °C) with FID detection and electronic peak integration (Hewlett–Packard HP 3380 A). The reactant master mixture consisted of about 1.0–1.5% of **4** [prepared from bicyclopropylidene (**3**)[5a] according to the published procedure[9]] and 1.5–2.0% of *n*-pentane as an internal standard diluted to about 400 Torr with N_2 in a 500-mL reservoir. Runs were carried out by admitting a known pressure of the mixture (16–30 Torr) into the pre-evacuated ($\leq$ 0.005 Torr) reaction vessel for a certain time. The reaction was quenched by sampling some of the reaction vessel contents with a pre-evacuated sample container, from which samples (diluted with about 30 Torr of N_2) could be injected into the gas chromatograph. After 2–3 runs, a blank analysis of the unused master mixture was performed to check the mass balance of the reaction. To rule out the influence of radical chain-reaction pathways, a run with about 5% propene as a radical scavenger was performed. For the test of surface influences, the reactor was replaced with another one filled with flame-

polished Pyrex tube cuttings which increased its surface area by a factor of ca. 16. The results are presented in Tables 2 and 3.

Table 2. Rearrangement of methylenespiropentane (**4**) to 1,2- and 1,3-dimethylenecyclobutane (**7** and **8**): proportions of **4** (%) and ratios $r = c(\mathbf{7})/c(\mathbf{8})$ as a function of time t [min] and temperature T [°C].

	t	0	50	100	220	350	540	810
T = 330.5	**4**	96.62	76.54	66.80	45.45	26.48	13.59	4.87
	r	–	1.63	3.10	3.28	3.24	3.00	2.99
	t	0	40	80	130	180	240	360
T = 340.5	**4**	96.77	72.35	54.02	38.31	26.53	17.55	6.86
	r	–	3.19	3.12	2.99	3.06	3.03	2.80
	t	0	20	40	60	90	123	180
T = 349.8	**4**	96.71	73.51	55.54	42.38	27.67	17.89	8.60
	r	–	2.84	2.74	2.81	2.87	2.82	2.70
	t	0	10	20	30	45	60	90
T = 359.2	**4**	97.09	75.29	58.65	45.32	32.6	22.39	11.15
	r	–	2.35	2.50	2.84	2.64	2.48	2.56
	t	0	5	10	15	23	30	45
T = 369.5	**4**	96.74	77.49	61.20	48.60	33.44	24.15	12.24
	r	–	2.73	2.55	2.49	2.58	2.50	2.50
	t	0	3	5	10	15	20	25
T = 379.2	**4**	96.62	76.89	65.84	43.07	29.96	20.10	14.38
	r	–	2.49	2.48	2.17	2.29	2.38	2.51

Table 3. Rearrangement of methylenespiropentane (**4**) to 1,2- and 1,3-dimethylenecyclobutane (**7** and **8**): proportions of **4** (%) and ratios $r = c(\mathbf{7})/c(\mathbf{8})$ as a function of reactor pressure p_i [Torr], surface area/volume ratio (s/v), and abundance of radical-chain-inhibiting agent (propene).

T [°C]	t [min]	p_i	Reactor	Propene	**4**	r
349.8	60	25	low s/v	–	42.38	2.81
349.9	60	79.5	low s/v	–	42.66	2.95
359.3	30	58	low s/v	–	45.32	2.84
359.3	30	29	high s/v	–	44.01	3.15
359.2	30	26.5	low s/v	20 equiv.	46.03	2.79

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[1] R. D. Bach, O. Dmitrenko, *J. Am. Chem. Soc.* **2004**, *126*, 4444–4452, and references therein.

[2] a) Reviews: P. Binger, H. M. Büch, *Top. Curr. Chem.* **1987**, *135*, 77–151; b) P. Binger, T. Schmidt, in: *Methods of Organic Chemistry (Houben-Weyl)*, 4th ed., vol. E17c (Ed.: A. de Meijere), Thieme, Stuttgart, **1997**, pp. 2217–2294; c) A. Brandi, A. Goti, *Chem. Rev.* **1998**, *98*, 589–635; d) A. Brandi, S. Cicchi, F. M. Cordero, A. Goti, *Chem. Rev.* **2003**, *103*, 1213–1269.

[3] Minireview: S. I. Kozhuskov, A. de Meijere, in: *Methods of Organic Chemistry (Houben-Weyl)*, 4th ed., vol. E17b (Ed.: A. de Meijere), Thieme, Stuttgart, **1997**, pp. 1695–1700.

[4] a) For modern theoretical considerations see: S. B. Lewis, D. A. Hrovat, S. J. Getty, W. T. Borden, *J. Chem. Soc., Perkin Trans. 2* **1999**, 2339–2347, and references cited therein; b) H. Ikeda, T. Nakamura, T. Miyashi, J. L. Goodman, K. Akiyama, S. Tero-Kubota, A. Houmam, D. D. M. Wayner, *J. Am. Chem. Soc.* **1998**, *120*, 5832–5833; c) J.-W. Pan, D. W. Rogers, F. J. McLafferty, *J. Mol. Struct. Theochem* **1999**, *468*, 59–66; d) A. B. Shtarov, P. J. Krusic, B. E. Smart, W. R. Dolbier Jr, *J. Org. Chem.* **2002**, *67*, 3464–3467; e) X. Creary, K. M. Miller, *Org. Lett.* **2002**, *4*, 3493–3496; f) H. Ikeda, H. Namai, H. Taki, T. Miyashi, *J. Org. Chem.* **2005**, *70*, 3806–3815; for considerations on the nature of strain in small-ring compounds, see: g) W. T. G. Johnson, W. T. Borden, *J. Am. Chem. Soc.* **1997**, *119*, 5930–5933 and ref.[1]

[5] Applying the reductive titanium-mediated cyclopropanation to methyl cyclopropanecarboxylate, the precursor to bicyclopropylidene (**3**) and thus this hydrocarbon itself have become readily available on a multigram scale: a) A. de Meijere, S. I. Kozhushkov, T. Späth, *Org. Synth.* **2000**, *78*, 142–151; b) A. de Meijere, S. I. Kozhushkov, T. Späth, N. S. Zefirov, *J. Org. Chem.* **1993**, *58*, 502–505; for reviews on the reductive titanium-mediated cyclopropanation, see also: c) O. G. Kulinkovich, A. de Meijere, *Chem. Rev.* **2000**, *100*, 2789–2834; d) O. Kulinkovich, *Eur. J. Org. Chem.* **2004**, 4517–4529.

[6] a) A. de Meijere, S. I. Kozhushkov, A. F. Khlebnikov, *Top. Curr. Chem.* **2000**, *207*, 89–147; b) A. de Meijere, S. I. Kozhushkov, *Eur. J. Org. Chem.* **2000**, 3809–3822; c) A. de Meijere, S. I. Kozhushkov, A. F. Khlebnikov, *Zh. Org. Khim.* **1996**, *32*, 1607–1626; *Russ. J. Org. Chem.* **1996**, *32*, 1555–1575; d) A. de Meijere, S. I. Kozhushkov, T. Späth, M. von Seebach, S. Löhr, H. Nüske, T. Pohlmann, M. Es-Sayed, S. Bräse, *Pure Appl. Chem.* **2000**, *72*, 1745–1756.

[7] a) J. K. Crandall, D. R. Paulson, C. A. Bunnell, *Tetrahedron Lett.* **1969**, *10*, 4217–4220; b) W. R. Dolbier Jr, K.-y. Akiba, *J. Chem. Soc. D* **1970**, 717–718; c) W. R. Dolbier Jr, K. Akiba, J. M. Riemann, C. A. Harmon, M. Bertrand, A. Bezaguet, M. Santelli, *J. Am. Chem. Soc.* **1971**, *93*, 3933–3940; d) R. R. Kostikov, A. P. Molchanov, I. A. Vasil'eva, Y. M. Slobodin, *J. Org. Chem. USSR (Engl. Transl.)* **1977**, *13*, 2361–2365; *Zh. Org. Khim.* **1977**, *13*, 2541–2547; e) W. R. Dolbier Jr, J. H. Alonso, *J. Am. Chem. Soc.* **1973**, *95*, 4421–4423.

[8] J. J. Gajewski, *Hydrocarbon Thermal Isomerizations*, 2nd ed., Academic Press, New York, **2004**.

[9] A. de Meijere, S. I. Kozhuskov, D. Faber, V. Bagutskii, R. Boese, T. Haumann, R. Walsh, *Eur. J. Org. Chem.* **2001**, 3607–3614.

[10] W. R. Dolbier Jr, *Tetrahedron Lett.* **1968**, *9*, 393–396.

[11] a) P. Le Perchec, J. M. Conia, *Tetrahedron Lett.* **1970**, *11*, 1587–1588; b) J. M. Denis, P. Le Perchec, J. M. Conia, *Tetrahedron* **1977**, *33*, 399–408; for a review on [*n*]rotanes, see: c) K. A. Lukin, N. S. Zefirov, in: *The Chemistry of the Cyclopropyl Group*, vol. 2 (Ed.: Z. Rappoport), Wiley, New York, **1995**, pp. 861–885.

[12] a) W. von E. Doering, J. C. Gilbert, *Tetrahedron Suppl.* **1966**, *7*, 397–414; b) P. N. Skancke, N. Koga, K. Morokuma, *J. Am. Chem. Soc.* **1989**, *111*, 1559–1563.

[13] M. C. Flowers, H. M. Frey, *J. Chem. Soc.* **1961**, 5550–5551.

[14] Dideuteriomethylenecyclopropane (E_a = 41.2 kcal mol^{-1}, lg A = 14.4) and 2,2-dimethylmethylenecyclopropane (E_a = 42.0 kcal mol^{-1}, lg A = 14.89): a) G. N. LeFevre, R. J. Crawford, *J. Org. Chem.* **1986**, *51*, 747–749; 2-methylmethylenecyclopropane (E_a = 40.4 kcal mol^{-1}, lg A = 14.26): b) J. P. Chesick, *J. Am. Chem. Soc.* **1963**, *85*, 2720–2723; 2,2,3,3-tetramethylmethylenecyclopropane (E_a = 36.4 kcal mol^{-1}, lg A = 14.27): c) R. J. Crawford, H. Tokunaga, *Can. J. Chem.* **1974**, *52*, 4033–4039.

[15] a) J. A. Kerr, A. Smith, A. F. Trotman-Dickenson, *J. Chem. Soc. A* **1969**, 1400–1403; b) R. Walsh, *Int. J. Chem. Kinet.* **1970**, *2*, 71–74.

[16] a) P. A. Arnold, B. K. Carpenter, *Chem. Phys. Lett.* **2000**, *328*, 90–96; b) D. J. Mann, W. L. Hase, *J. Am. Chem. Soc.* **2002**, *124*, 3208–3209; c) K. Liu, H.-M. Zhao, S.-Y. Ma, Z.-H. Li, *J. Mol. Struct. (Theochem)* **2004**, *612*, 209–213.

[17] a) P. v. R. Schleyer, J. E. Williams, K. R. Blanchard, *J. Am. Chem. Soc.* **1970**, *92*, 2377–2386; b) H.-D. Beckhaus, C. Rüchardt, S. I. Kozhushkov, V. N. Belov, S. P. Verevkin, A. de Meijere, *J. Am. Chem. Soc.* **1995**, *117*, 11854–11860.
[18] For reviews, see: a) A. L. J. Beckwith, K. U. Ingold, in: *Rearrangements in Ground and Excited States*, vol. 1 (Ed.: P. de Mayo), Academic Press, New York, **1980**, pp. 161–310; b) L. C. Walton, in: *Methods of Organic Chemistry (Houben-Weyl)*, 4th ed., vol. E17c (Ed.: A. de Meijere), Thieme, Stuttgart, New York, **1997**, pp. 2438–2525.
[19] T. S. Chambers, G. B. Kistiakowsky, *J. Am. Chem. Soc.* **1934**, *56*, 399–405.
[20] S. Arora, P. Binger, *Synthesis* **1974**, 801–803.
[21] A. de Meijere, K. Ernst, B. Zuck, M. Brandl, S. I. Kozhushkov, M. Tamm, D. S. Yufit, J. A. K. Howard, T. Labahn, *Eur. J. Org. Chem.* **1999**, 3105–3115.

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