

## Reviews

### Cyclopropylidenes, bicyclopropylidenes, and vinylcarbenes — some modes of formation and preparative applications\*

A. de Meijere,<sup>a\*</sup> H. Schill,<sup>a</sup> S. I. Kozhushkov,<sup>a</sup> R. Walsh,<sup>b</sup> E. M. Müller,<sup>c</sup> and H. Grubmüller<sup>c</sup>

<sup>a</sup>Institute of Organic and Biomolecular Chemistry, Georg August University,  
Tammannstrasse 2, D-37077 Göttingen, Germany. \*\*

Fax: +49 (0) 551 39 9475. E-mail: Armin.deMeijere@chemie.uni-goettingen.de

<sup>b</sup>Department of Chemistry, University of Reading,  
Whiteknights, P.O. Box 224, Reading RG6 6AD, Great Britain.

E-mail: R.Walsh@reading.ac.uk

<sup>c</sup>Theoretical Molecular Biophysics Group, Max-Planck-Institute for Biophysical Chemistry,  
Am Faßberg 11, D-37077 Göttingen, Germany

The routes of transformation of the simplest bicyclopropylidene into the derivatives of the second and third generations and synthesis of perspirocyclopropanated [3]rotane and linear spiral [4]- and [5]triangulanes are discussed.

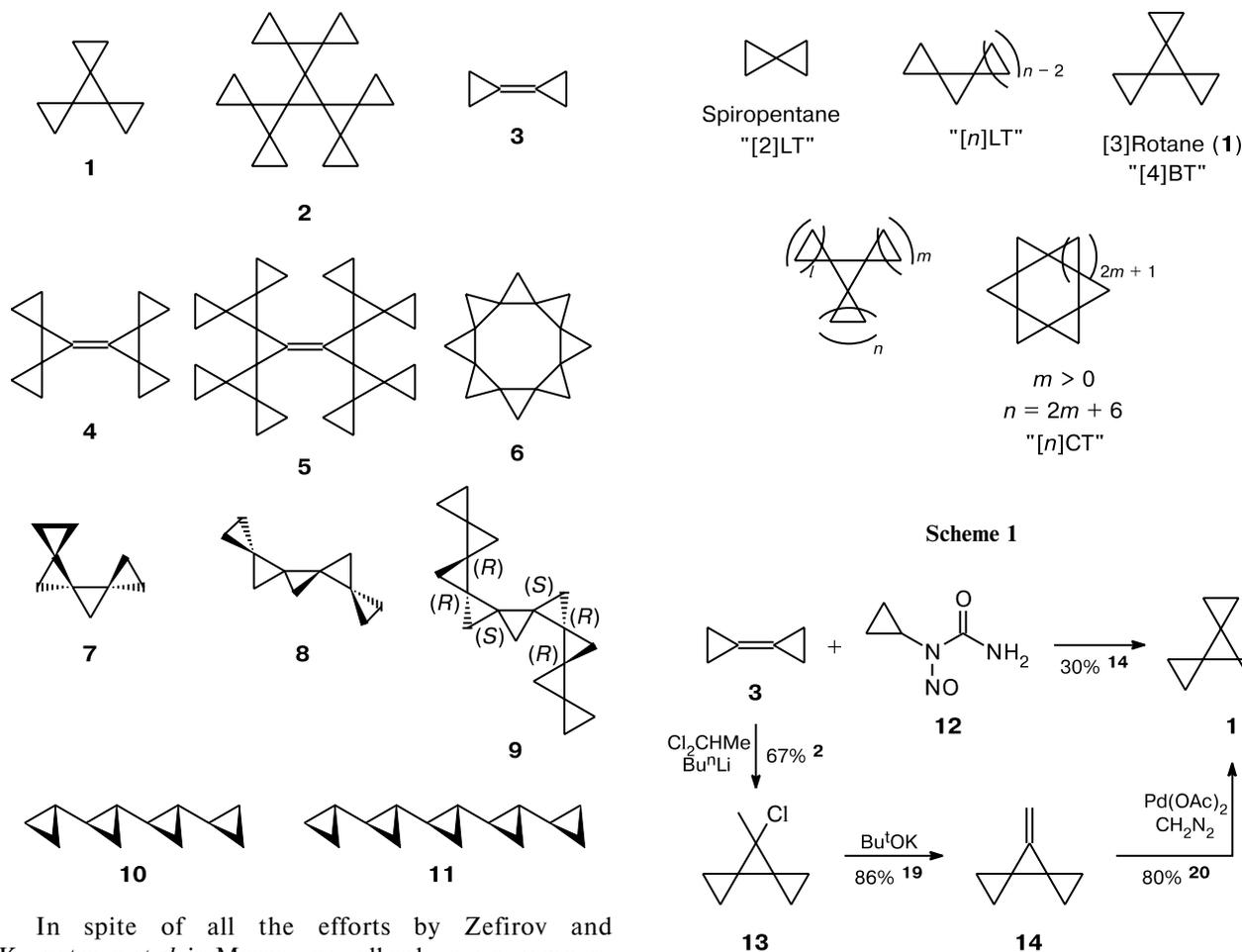
**Key words:** cyclopropylidenes, bicyclopropylidenes, vinylcarbenes, perspirocyclopropanated [3]rotane, linear spiral [4]- and [5]triangulanes.

Aggregates **1–11** with double bonded and spirofused cyclopropane rings have intrigued us for more than 30 years.<sup>1</sup> They all suffer from increased strain<sup>2</sup> and thereby should show unique and enhanced reactivities.<sup>3–5</sup> For bicyclopropylidene (**3**), this has been demonstrated in a number of ways<sup>6–9</sup> and even quantified by the kinetics of its bromination.<sup>10</sup> Our own first synthesis of **3**<sup>8</sup> was

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\*\* Institut für Organische und Biomolekulare Chemie der Georg-August-Universität Göttingen, Tammannstrasse 2, D-37077 Göttingen, Germany.

not much better than the first published synthesis by Conia *et al.*,<sup>11</sup> but — after a number of improvements had been made by Conia *et al.* and by our group<sup>12</sup> — eventually we were able to develop a really productive synthesis of this unique C<sub>6</sub>H<sub>8</sub> hydrocarbon, which is easily reproducible and also scalable to multikilogram quantities.<sup>13</sup> In the meantime, we have created accesses to the second-generation bicyclopropylidene **4** and even the third-generation derivative — speaking in terms of dendrimers — **5**. Modern synthetic methodology makes it possible to go far beyond [3]rotane **1**<sup>14</sup> in terms of spiroaggregation up to perspirocyclopropanated [3]rotane **2**.<sup>15</sup>



In spite of all the efforts by Zefirov and Kuznetsova *et al.* in Moscow as well as by our own group, cyclic structure **6** remains elusive. However, we have been able to prepare [4]- and [5]triangulanes **7** and **8** in enantiomerically pure forms, and we are well on our way to access even enantiomerically pure linear [9]triangulane **9**. When we were engaged in the conformational analysis of bicyclopropyl some 40 years ago,<sup>16</sup> we did not anticipate that this investigation would ever have any relevance to natural products chemistry. Indeed, nature produces compounds which contain fatty acid residues with four and even five consecutive cyclopropyl groups as in **10** and **11**, respectively.<sup>17</sup>

Hydrocarbons which consist of spirofused cyclopropyl groups only, have been termed  $[n]$ triangulanes, in which  $n$  designates the number of spirofused rings.<sup>18</sup> Spiropentane is the smallest member in this class of compounds. Further spirolinkage of cyclopropyl groups can lead to linear (LT), branched (BT) and even cyclic triangulanes (CT).

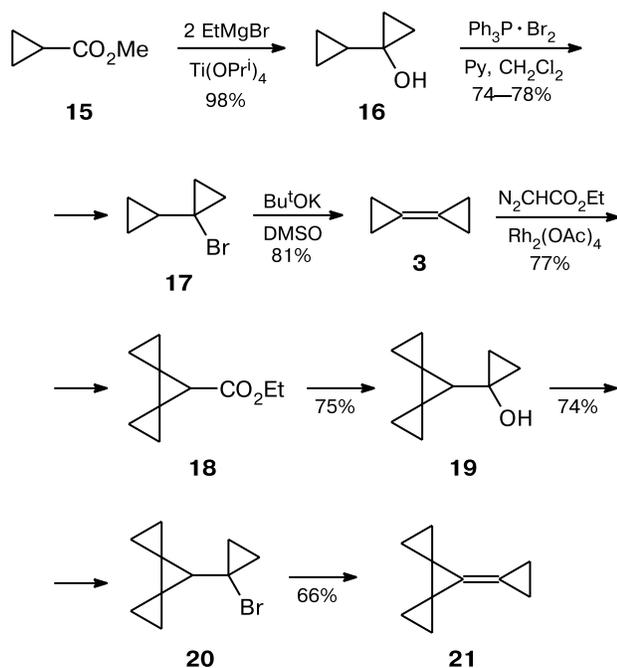
[3]Rotane **1** is a particular case of a branched [4]triangulane. It was first synthesized by Conia *et al.* by cyclopropanation of bicyclopropylidene (**3**) with diazocyclopropane generated *in situ* from *N*-nitrosocyclopropylurea (**12**).<sup>14</sup>

A better access was later developed by Erden<sup>19</sup> and Zefirov *et al.*<sup>20</sup> The key step in this approach is the addition of chloromethylcarbene onto bicyclopropylidene (**3**) to yield **13** (see Scheme 1). The dehydrochlorination with potassium *tert*-butoxide leads to 7-methylenedisp[iro[2.0.2.1]heptane which is cyclopropanated with diazomethane under palladium acetate catalysis.

The essential precursor to [3]rotane **1**, bicyclopropylidene **3**, is now easily produced in multigram or even kilogram quantities by the drastically improved synthesis starting from methyl cyclopropanecarboxylate (**15**). Utilizing the conversion of esters to cyclopropanols by treatment with two equivalents of ethylmagnesium bromide in the presence of titanium tetrakisoperoxide according to Kulinkovich *et al.*,<sup>21</sup> **15** furnishes 1-cyclopropylcyclopropanol (**16**) in virtually quantitative yield (Scheme 2). This cyclopropanol is converted to bromide **17** by treatment with the triphenylphosphine dibromide complex in methylene chloride in the presence of pyridine, and the resulting bromide **17** is dehydrobrominated with potassium *tert*-butoxide in DMSO.<sup>13</sup>

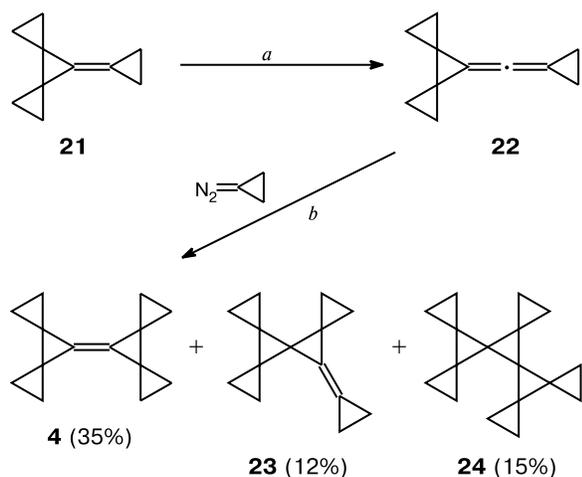
Bicyclopropylidene (**3**) is also the key intermediate *en route* to perspirocyclopropanated (second-generation)

Scheme 2



bicyclopropylidene **4**, the third-generation bicyclopropylidene **5** and perspirocyclopropanated [3]rotane **2**. The best way to get to all these exotic structures is to cyclopropanate bicyclopropylidene (**3**) with ethyl diazoacetate under dirhodium tetraacetate catalysis (see Scheme 2), converting the resulting ethyl dispiro[2.0.2.1]heptane-7-carboxylate (**18**) by a Kulinkovich reaction to cyclopropylidene alcohol **19**, and transforming this *via* bromide **20** to dispirocyclopropanated bicyclopropylidene **21**.<sup>22</sup>

Scheme 3

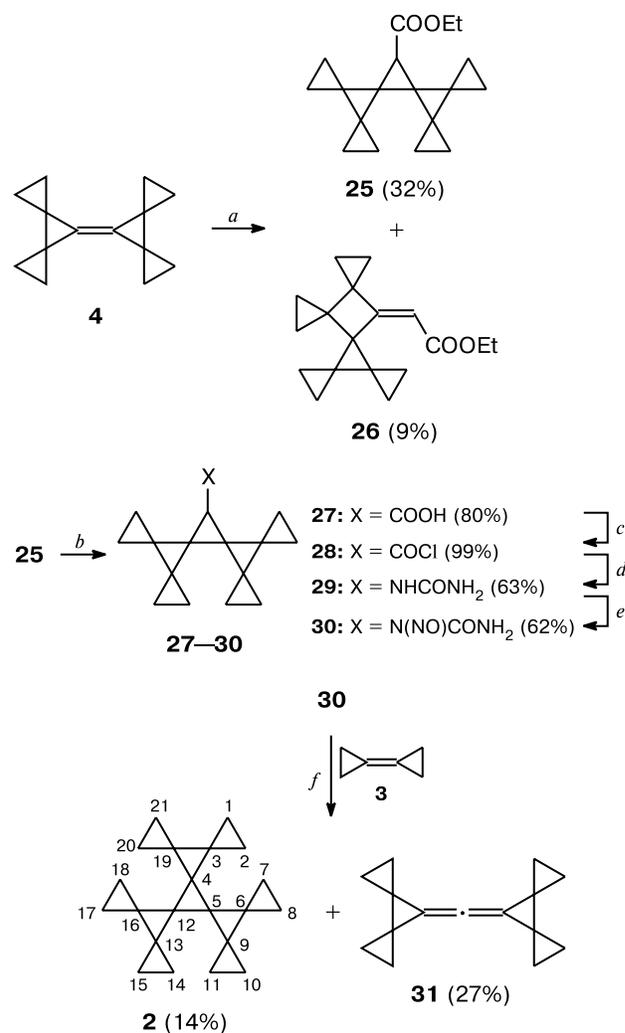


**Reagents and conditions:** a. 1)  $\text{CHBr}_3$ ,  $\text{NaOH}$ ,  $\text{BnEt}_3\text{NCl}$ ,  $\text{CH}_2\text{Cl}_2$ , 3 h,  $60^\circ\text{C}$ , 80%, 2)  $\text{MeLi}$ ,  $\text{Et}_2\text{O}$ ,  $0^\circ\text{C}$ , 80%; b. Pentane,  $0^\circ\text{C}$ , 8 h, conversion 68%.

The latter alkene, which had previously been prepared by Fitjer,<sup>23</sup> can be extended to allene **22** by the Doering–Skattebøl–Moore protocol, *i.e.*, dibromocarbene addition and treatment of the resulting dibromocyclopropanation product with methyllithium in ether (Scheme 3).<sup>24</sup>

Upon cyclopropanation of **22** with *in situ* generated diazocyclopropane, perspirocyclopropanated bicyclopropylidene **4** was obtained in 35% yield along with regioisomeric cyclopropanation product **23** and tetraspirocyclopropanated [3]rotane **24**, a branched [8]triangulane, resulting from twofold cyclopropanation of allene **22** with diazocyclopropane.<sup>24,25</sup>

Scheme 4

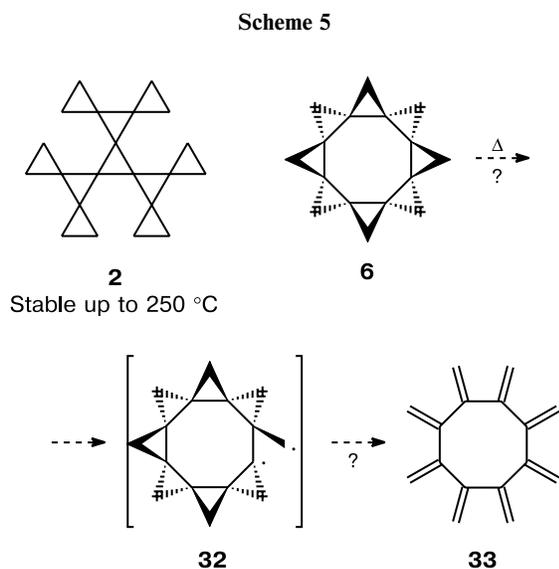


**Reagents and conditions:** a. 2  $\text{N}_2\text{CHCO}_2\text{Et}$ ,  $\text{CH}_2\text{Cl}_2$ ,  $[\text{Rh}(\text{OAc})_2]_2$  (1 mol.%),  $0^\circ\text{C}$ , 12 h; b. 1.2  $\text{NaOH}$ ,  $\text{H}_2\text{O}$ ,  $100^\circ\text{C}$ , 6 h; c.  $\text{SOCl}_2$ ,  $80^\circ\text{C}$ , 2 h; d. 1)  $\text{NaN}_3$ ,  $\text{Me}_2\text{CO}$ , 2 h; 2)  $\text{C}_6\text{H}_6$ ,  $80^\circ\text{C}$ , 2 h; 3)  $\text{NH}_3$ ; e.  $\text{N}_2\text{O}_4$ ,  $\text{Et}_2\text{O}$ ,  $0^\circ\text{C}$ , 2 h; f. 10  $\text{NaOMe}$ ,  $0^\circ\text{C}$ , 10 h.

Perspirocyclopropanated bicyclopropylidene **4** served as the starting material for perspirocyclopropanated [3]rotane,  $D_{3h}$ -symmetric branched [10]triangulane **2**.<sup>15,25</sup> Although this synthesis looks quite straightforward, it was realized only after four attempted alternative routes had failed. Cyclopropanation of **4** with ethyl diazoacetate under dirhodium tetraacetate catalysis gave ethyl [7]triangulancarboxylate **25** as the main product (Scheme 4).

Acid **27** obtained by hydrolysis was converted to acid chloride **28**. This in turn was converted to urea **29** which was nitrosated to diazo[7]triangulane precursor **30**. The *in situ* generation of this diazo[7]triangulane by treatment of nitrosourea **30** with a slurry of sodium methoxide in pentane and bicyclopropylidene (**3**) gave desired perspirocyclopropanated [3]rotane **2** along with tetraspirocyclopropanated dicyclopropylidenemethane **31**.

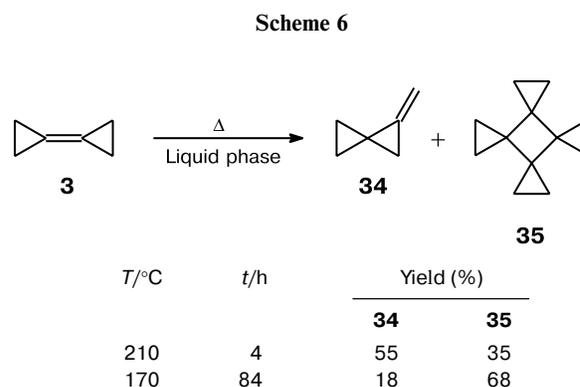
Unique hydrocarbon **2** has some remarkable features. Electronic interaction between the spirolinked cyclopropane units leads to a significant bond shortening of the central cyclopropane ring. Considering the total strain energy of this molecule consisting of ten cyclopropane rings and nine spiro carbon atoms with strain increments of 28.1 and 8.4 kcal mol<sup>-1</sup>, respectively,<sup>2</sup> adding up to a total of 356.6 kcal mol<sup>-1</sup>, this hydrocarbon is extraordinary stable. It can be heated up to 250 °C without decomposition (Scheme 5). The reason for this kinetic stability arises from the fact that the ring-opening of any of the cyclopropyl bonds in **2** requires about the same activation energy as the ring-opening of a simple 1,2-disubstituted cyclopropane derivative, and that is approximately 60 kcal mol<sup>-1</sup>,<sup>26</sup> since none of the possible 1,3-diradicals formed by opening of a strained bond in **2** experiences any particular stabilization.



For the same reason, the yet unknown cyclo[8]triangulane **6** should be an isolable molecule in spite of its

extrapolated strain energy of 292 kcal mol<sup>-1</sup>. The ring-opening of, e.g., an external cyclopropane bond in **6** would also require about the same activation energy, but once this would have happened to give 1,3-diradical **32**, the molecule would rapidly unzip to [8]radialene **33** (see Scheme 5).

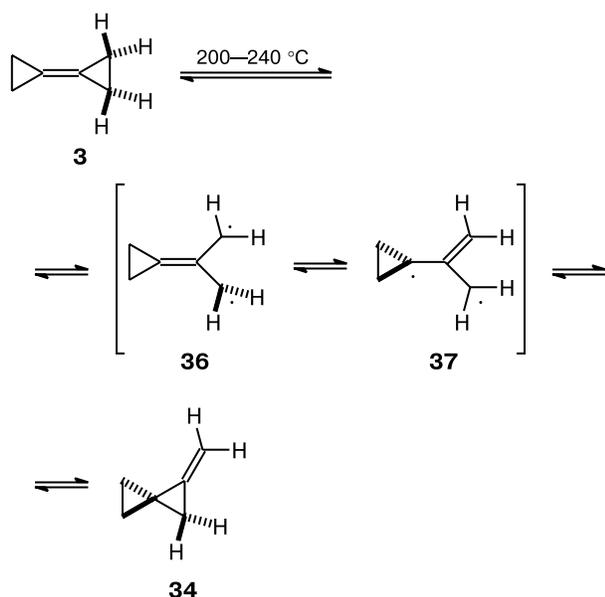
What can really happen upon thermolysis of such complex triangulanes is completely unknown. Even the thermolysis of [3]rotane **1** had not been studied, and therefore we embarked on an investigation of the thermal rearrangement of this compound as a first model. To test a newly developed computational method for the prediction of unimolecular chemical reactions by so-called "chemical flooding",<sup>27</sup> we first studied the thermal rearrangement of the even simpler molecule bicyclopropylidene (**3**) in the gas phase. It was already known from the work of Conia *et al.*<sup>28</sup> that **3**, when heated in the liquid phase, undergoes rearrangement to methylenespiropentane (**34**) and dimerization to [4]rotane **35**.<sup>29</sup> The product distribution apparently depends on the reaction temperature and it should also depend on the concentration (Scheme 6).



In the gas phase, **3** rearranges completely unimolecularly with an activation energy of 39.2±0.7 kcal mol<sup>-1</sup> (logA = 14.02±0.33) to methylenespiropentane **34**, and this rearrangement turned out to be reversible with the equilibrium mixture containing 95% of **34** and 5% of **3**.<sup>30</sup> "Chemical flooding" computations showed that the first ring-opening of **3** occurs at one of the distal bonds with concomitant rotation of one of the CH<sub>2</sub> groups to give the orthogonal trimethylenemethane diradical **36** (Scheme 7). After internal rotation to bond-tautomeric trimethylenemethane diradical **37**, ring closure occurs to give **34**.<sup>27</sup>

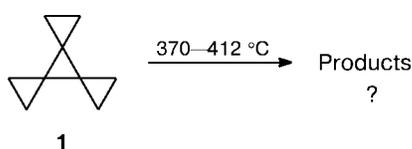
In a collaborative effort between our own group in Göttingen, the computational experts H. Grubmüller and E. M. Müller in Göttingen as well as the specialist for gas-phase kinetics R. Walsh in Reading, England, we studied the thermal degradation of [3]rotane **1**. In the gas-phase kinetic work, we initially could not identify any products, but we determined the Arrhenius activation parameters

Scheme 7



for the overall disappearance of **1** as  $E_a = 56.5 \pm 1.5$  kcal mol<sup>-1</sup> and  $\log A = 15.1 \pm 0.47$  (Scheme 8).

Scheme 8

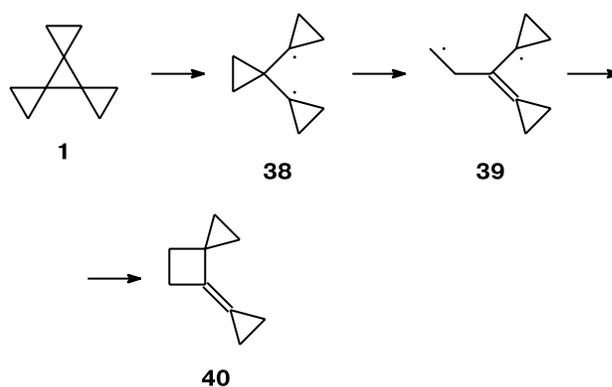


This confirms the above-mentioned anticipation that any rearrangement of compounds like **1** must start with a homolytic cleavage of a cyclopropyl single bond, and this cleavage is not significantly facilitated compared to that of simple 1,1- or 1,2-disubstituted cyclopropane derivatives.<sup>26</sup>

There are only three possible modes of initial ring opening for the thermal rearrangement and/or decomposition of **1**. The first one starts with a bond cleavage in the central ring to give diradical **38**. With this bond cleavage, the molecule releases approximately 54 kcal mol<sup>-1</sup> of ring strain energy (SE), since one cyclopropane ring (SE = 28.1 kcal mol<sup>-1</sup>) is opened and three spiroentyl spirocarbons are removed (SE increment = 8.5 kcal mol<sup>-1</sup> each). Diradical **38** then opens up one of the cyclopropyl groups to get from a cyclopropylcarbinyl to a homoallyl moiety as in **39** (Scheme 9). The latter, by simple intramolecular recombination, would yield 4-cyclopropylidenespiro[2.3]hexane (**40**).

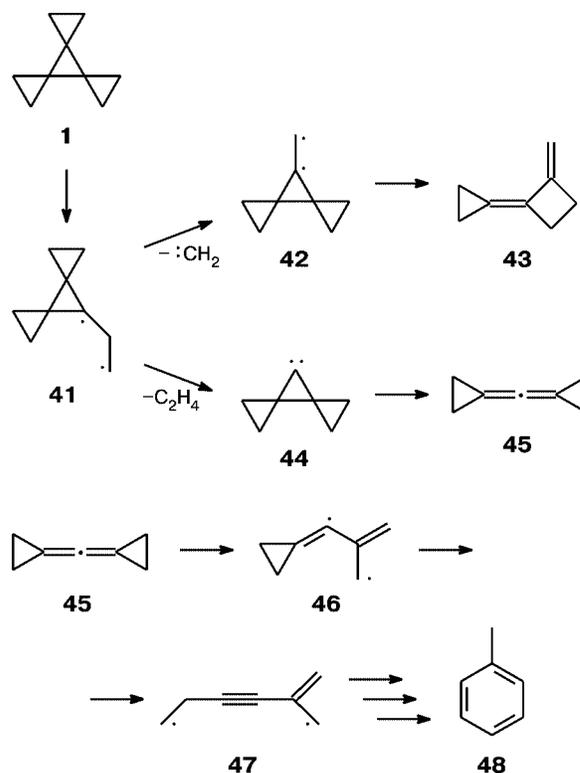
The second mode (Scheme 10) starts with the cleavage of one of the proximal bonds of the outer cyclopropane rings to give biradical **41**, which apparently has two

Scheme 9



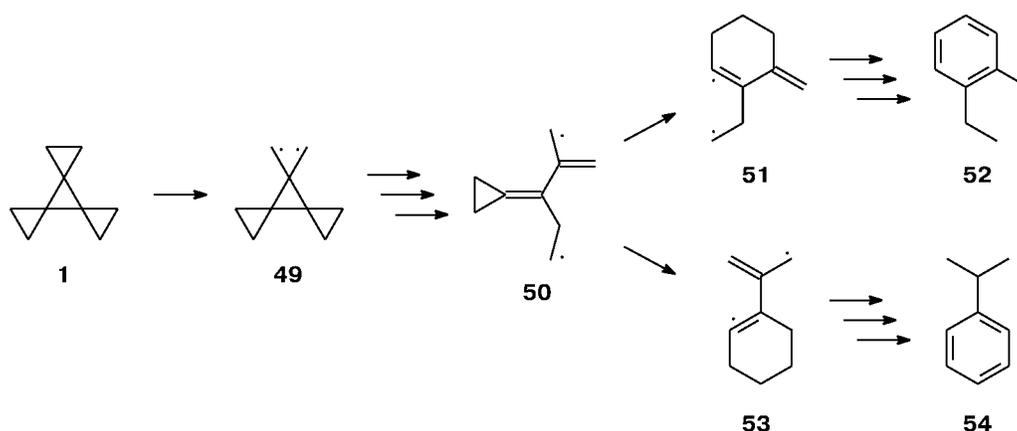
choices for further reaction. It can split off methylene and yield 1,2-diradical **42** which, along several further steps, eventually rearranges to 2-cyclopropylidenemethylene-cyclobutane **43**.

Scheme 10



The other choice of intermediate diradical **41** is to split off ethylene providing 7-dispiroheptylidene **44** which cycloreverses to dicyclopropylidenemethane (**45**). It is not surprising that the sensitive C<sub>7</sub>H<sub>8</sub> hydrocarbon **45** could not be detected in the pyrolysate, but only its stabilomer toluene (**48**), which can be rationalized as being formed via diradicals **46** and **47**. Although there certainly may be

Scheme 11

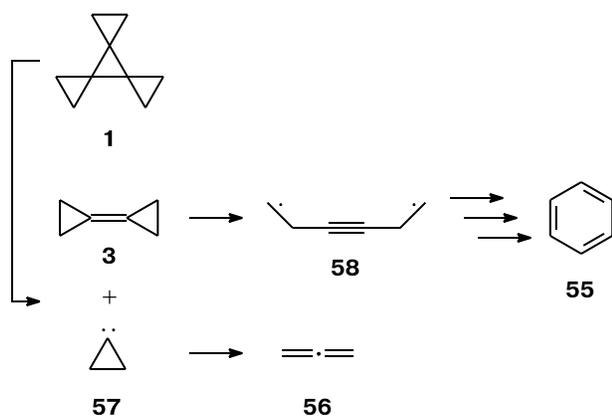


other explanations for the formation of ethylene, the fact that ethylene was indeed detected in the pyrolysate and quantified as dibromoethane after addition of bromine to the crude pyrolysate, may be taken as an indication that this predicted pathway has some relevance.

The third mode of initial ring opening is the cleavage of a distal bond of one of the outer cyclopropane groups giving 1,3-diradical **49**, which, in a number of rearrangement steps, can lead to **50** (Scheme 11). It is highly speculative, how this eventually arrives at 2-methylethylbenzene (**52**) and isopropylbenzene (**54**), respectively, but these two aromatic products were identified after the thermolysis (Scheme 11).

Benzene (**55**) and allene (**56**) were also identified among the products, and these might be formed from bicyclopropylidene (**3**) and cyclopropylidene (**57**) resulting from a *retro*-cheletropic cleavage of [3]rotane **1** (Scheme 12).\*

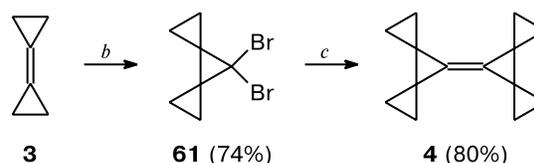
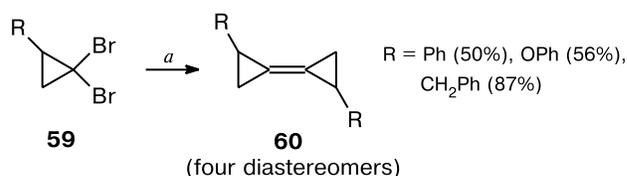
Scheme 12



\* Some of these modes of degradation of [3]rotane **1** are confirmed by computer simulations: E. M. Müller and H. Grubmüller, unpublished data.

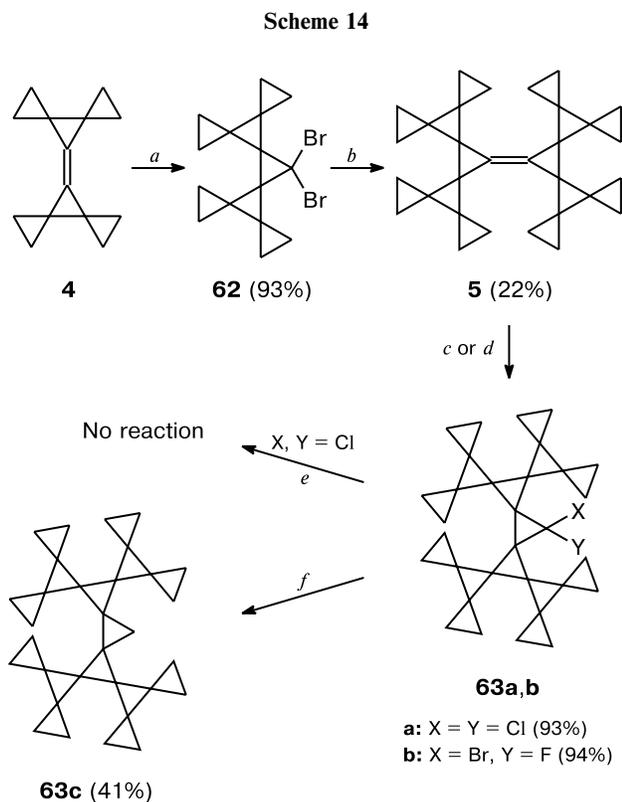
The highly efficient dimerization of bromocoppercarbenoids generated from dibromocyclopropanes **59** by treatment with *n*-butyllithium in tetrahydrofuran in the presence of cupric chloride to yield bicyclopropylidenes **60**, as developed by Neuenschwander *et al.*,<sup>31</sup> made perspirocyclopropanated bicyclopropylidene **4**, the second-generation dendrimer in the family of bicyclopropylidenes (Scheme 13), much more easily available in large quantities than before.<sup>32</sup>

Scheme 13



**Reagents and conditions:** *a.* Bu<sup>n</sup>Li, THF (0.3 mol L<sup>-1</sup>), CuCl<sub>2</sub> (0.1 equiv.), -95 °C, 1 h, then ~20 °C, 1 h; *b.* CHBr<sub>3</sub>, KOH, BnEt<sub>3</sub>NCl, 20 °C, 6 h; *c.* Bu<sup>n</sup>Li, THF (0.5 mol L<sup>-1</sup>), CuCl<sub>2</sub> (0.1 equiv.), -100 °C → -90 °C, 2 h.

Upon treatment of 7,7-dibromodispiro[2.0.2.1]heptane (**61**), which is easily obtained by dibromocarbene addition to bicyclopropylidene (**3**), with *n*-butyllithium under these conditions, hydrocarbon **4** is obtained in 80% yield. With gram quantities of **4** available, dibromocarbene adduct **62** was prepared in 93% yield and then treated with *n*-butyllithium in the presence of cupric chloride to furnish the third-generation bicyclopropylidene **5** in 22% yield (Scheme 14).<sup>25,33</sup>

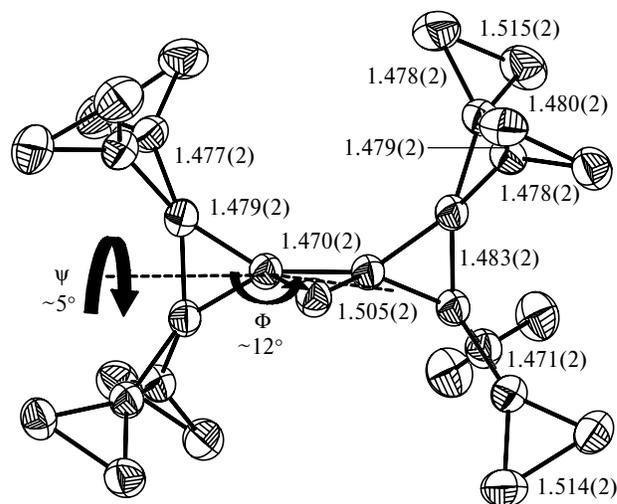


**Reagents and conditions:** *a.*  $\text{CHBr}_3$ , KOH,  $\text{BnEt}_3\text{NCl}$ ,  $\text{CH}_2\text{Cl}_2$ ,  $0\text{ }^\circ\text{C} \rightarrow 30\text{ }^\circ\text{C}$ , 5 h; *b.*  $\text{Bu}^n\text{Li}$ , THF ( $0.5\text{ mol L}^{-1}$ ),  $\text{CuCl}_2$  (0.1 equiv.),  $-100\text{ }^\circ\text{C} \rightarrow -90\text{ }^\circ\text{C}$ , 2 h, then  $-20\text{ }^\circ\text{C}$ , 1 h; *c.* 50% NaOH,  $\text{CHCl}_3$ ,  $\text{BnEt}_3\text{NCl}$ ,  $\sim 20\text{ }^\circ\text{C}$ , 3 days; *d.* 50% NaOH,  $\text{CHBr}_2\text{F}$ ,  $\text{CH}_2\text{Cl}_2$ ,  $\text{BnEt}_3\text{NCl}$ ,  $\sim 20\text{ }^\circ\text{C}$ , 3 days; *e.*  $\text{Bu}^n\text{Li}$ ,  $\text{CuCl}_2$ ; *f.* Li, THF,  $\text{Bu}^t\text{OH}$ ,  $15\text{--}20\text{ }^\circ\text{C}$ , 3 days.

The double bond in **5** is sterically highly encumbered, so that dibromocarbene addition failed. However, dichlorocarbene and bromofluorocarbene addition gave the corresponding dihalocyclopropanes **63a,b** in virtually quantitative yields. The dichloro derivative did not react with *n*-butyllithium in the presence of cupric chloride. It could, however, be reduced with lithium in tetrahydrofuran in the presence of *tert*-butyl alcohol to furnish the highest ever made [*n*]triangulane **63c** with 15 spirocyclopropane units (see Scheme 14).<sup>25,33</sup>

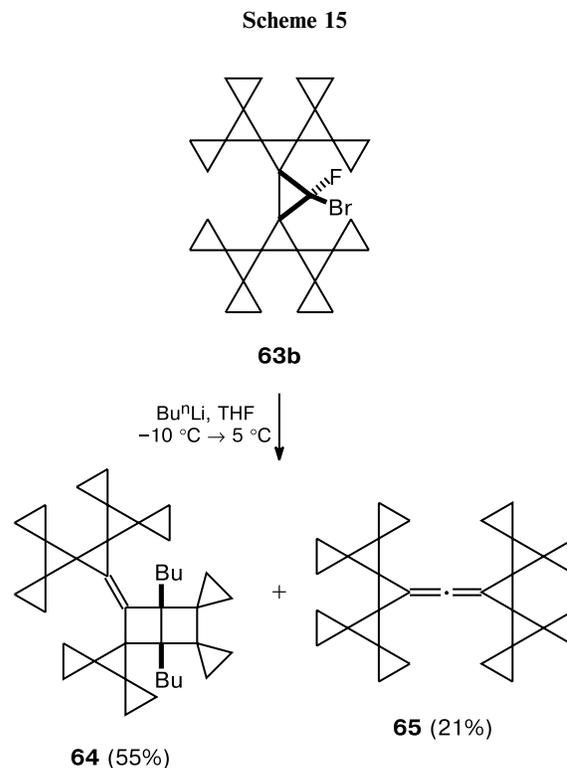
Crystal structure analyses were obtained for all three compounds **63a–c**, and they all show one remarkable structural feature, as exemplified by the [15]triangulane hydrocarbon (Fig. 1). Due to the steric interaction of the left and right halves on the back side of the molecule, the central spiro-pentane units are distorted in two ways. The axis is bent by  $5^\circ$ , and the two spirocyclopropane rings in each spiro-pentane unit are twisted by  $12^\circ$ , apparently to reduce the repulsive van der Waals interactions.<sup>33</sup>

Upon treatment of bromofluoro derivative **63b** with *n*-butyllithium in the presence of cupric chloride, a complicated mixture of unidentified products was obtained. However, upon treatment of the same compound **63b**



**Fig. 1.** Crystal structure of new branched [15]triangulane **63c**; interatomic distances are given in Å.

with *n*-butyllithium in tetrahydrofuran at  $-10$  to  $+5\text{ }^\circ\text{C}$ , the third-generation dicyclopropylidenemethane **65** was obtained in 21% and the unusual oligospirocyclopropanated 1,4-dibutyl-2-cyclopropylidenebicyclo[2.2.0]hexane **64** was isolated in 55% yield. Both structures were rigorously proved by X-ray crystal structure analyses (Scheme 15).<sup>25</sup>



Although the formation of **64** is not straightforward, it can very well be rationalized on the basis of literature

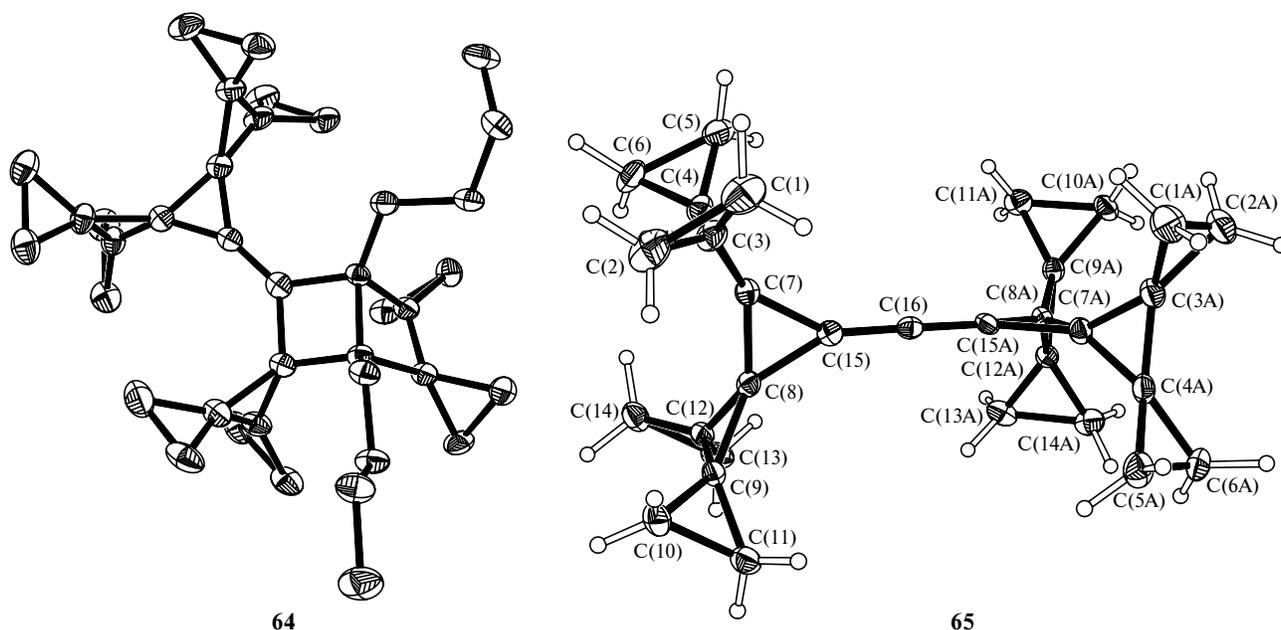


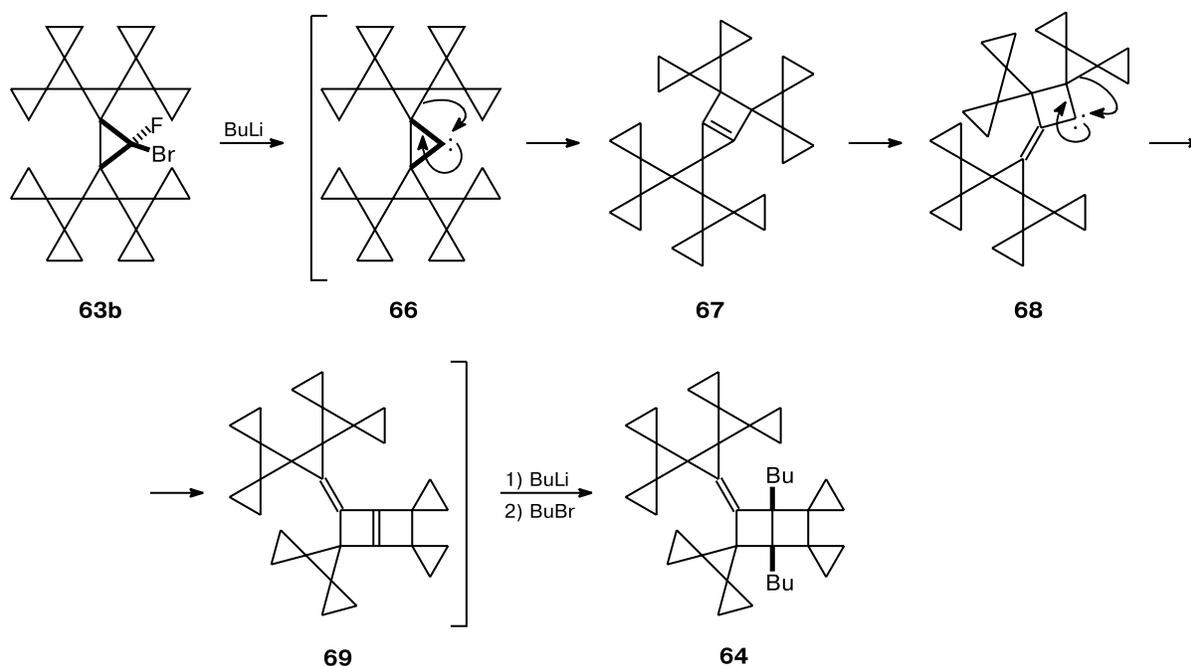
Fig. 2. Structures of compounds **64** and **65** from X-ray diffraction data.<sup>25</sup>

precedences for the behavior of cyclopropylmethylenes, cyclopropenes, and highly strained bicyclo[2.2.0]hex-1(4)-enes (Scheme 16).

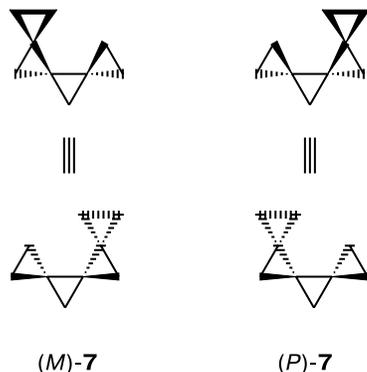
The carbenoid formed from bromofluorocyclopropane **63b** with *n*-butyllithium probably undergoes  $\alpha$ -elimination to give free carbene **66**, which, being a cyclopropylidene and at the same time a cyclopropylmethylene, undergoes ring expansion to yield highly strained bi-

cyclo[2.1.0]pent-1(4)-ene **67**. The cyclopropene moiety in this hydrocarbon ring opens up to give vinylcarbene **68** which at the same time is a cyclopropylmethylene again and undergoes ring expansion to yield the bicyclo[2.2.0]hex-1(4)-ene **69**. The latter adds *n*-butyllithium, and the resulting butylated bridgehead lithium derivative reacts with the previously formed butyl bromide to give dibutyl-substituted product **64**.

#### Scheme 16

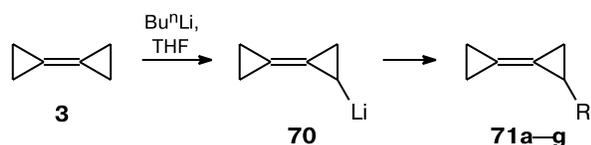


Linear  $[n]$ triangulanes with  $n > 3$  have another remarkable feature in that they are chiral. It occurred to us that it would be worthwhile to prepare such compounds in enantiomerically pure forms and study their properties. As a first goal, we chose [4]triangulane and set out to prepare either one of the enantiomers (*M*)-7 or (*P*)-7.



As a starting material, we chose bicyclopropylidene (**3**), which already contains two of the three-membered rings for the target molecule. Not only is parent hydrocarbon **3** readily available,<sup>13</sup> it can also easily be functionalized by deprotonation with *n*-butyllithium in tetrahydrofuran and subsequent electrophilic substitution of lithio derivative **70**. A large series of substituted bicyclopropylidenes **71** has been prepared in this way (Scheme 17).<sup>34</sup>

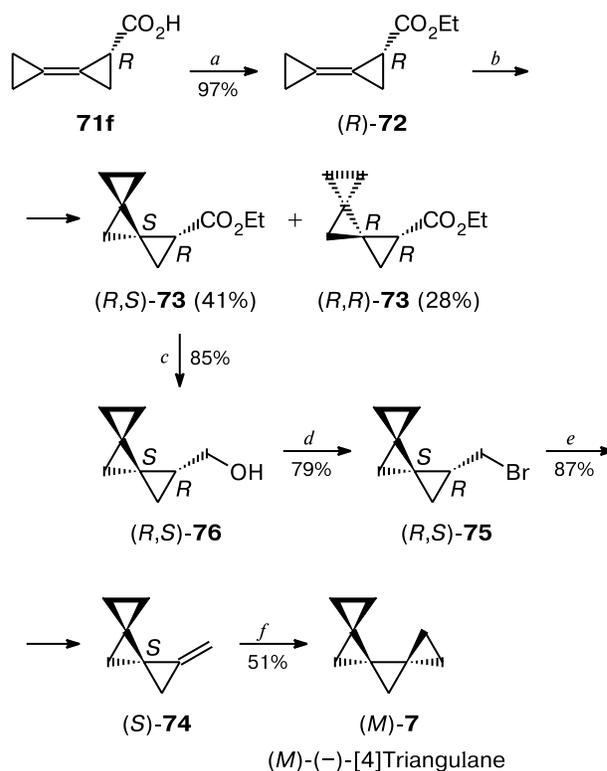
Scheme 17



Reagent	Compound <b>71</b>	R	Yield (%)
Me <sub>3</sub> SiCl	<b>a</b>	Me <sub>3</sub> Si	85
(PhS) <sub>2</sub>	<b>b</b>	PhS	77
C <sub>2</sub> Cl <sub>6</sub>	<b>c</b>	Cl	73
(CH <sub>2</sub> Br) <sub>2</sub>	<b>d</b>	Br	65
<i>n</i> -C <sub>7</sub> H <sub>15</sub> I	<b>e</b>	C <sub>7</sub> H <sub>15</sub>	74
1) CO <sub>2</sub> , 2) H <sup>+</sup>	<b>f</b>	COOH	95
Me <sub>2</sub> CO	<b>g</b>	Me <sub>2</sub> C(OH)	82

Carboxylic acid **71f** was obtained in particularly good yield (95%). It was converted to ethyl ester **72** (Scheme 18), which was cyclopropanated according to the Simmons-Smith protocol to give a mixture of diastereomeric ethyl [3]triangulancarboxylates (*R,S*)-**73** and (*R,R*)-**73**. These diastereomers could easily be separated, pure (*R,S*)-**73** was reduced to alcohol **76**, the latter converted to bromide **75** and this dehydrobrominated by treatment with potassium *tert*-butoxide in dimethylsulfoxide to give enantiomerically pure methylene[3]triangulane **74**.

Scheme 18



**Reagents and conditions:** a. BF<sub>3</sub>·Et<sub>2</sub>O, EtOH, 78 °C, 2 h; b. CH<sub>2</sub>I<sub>2</sub>, Zn, DME, ultrasound, 80 °C, 2 h; c. LiAlH<sub>4</sub>, Et<sub>2</sub>O; d. Ph<sub>3</sub>P·Br<sub>2</sub>, Py, CH<sub>2</sub>Cl<sub>2</sub>, -10 °C, 1.5 h, then 20 °C, 7 h; e. Bu<sup>t</sup>OK, DMSO, 20 °C, 14 h; f. CH<sub>2</sub>N<sub>2</sub>, Pd(OAc)<sub>2</sub>, Et<sub>2</sub>O, -5 °C.

Cyclopropanation of **74** with diazomethane under palladium acetate catalysis led to the enantiomerically pure (*M*)-(-)-[4]triangulane (*M*)-7. The specific rotation of triangulane (*M*)-7 is presented below.

λ/nm	-[α] <sub>D</sub> <sup>20</sup>	
	Experiment	DFT/SCI calculation
589	192.7	241.0
578	201.3	250.2
546	229.7	283.8
436	400.2	466.0
365	648.2	703.7

The absolute configuration of [4]triangulane (*M*)-7 was assigned on the basis of the absolute configuration of the starting material **71f**, which was established by an X-ray crystal-structure analysis of its (*R*)-α-phenylethylamide.

To our surprise, this formally saturated hydrocarbon without any chromophoric group, which is transparent in the UV region down to 200 nm, has a specific rotation at 589 nm of about 200.<sup>35</sup> This is the expression of an extremely high amplitude Cotton effect below 200 nm, which

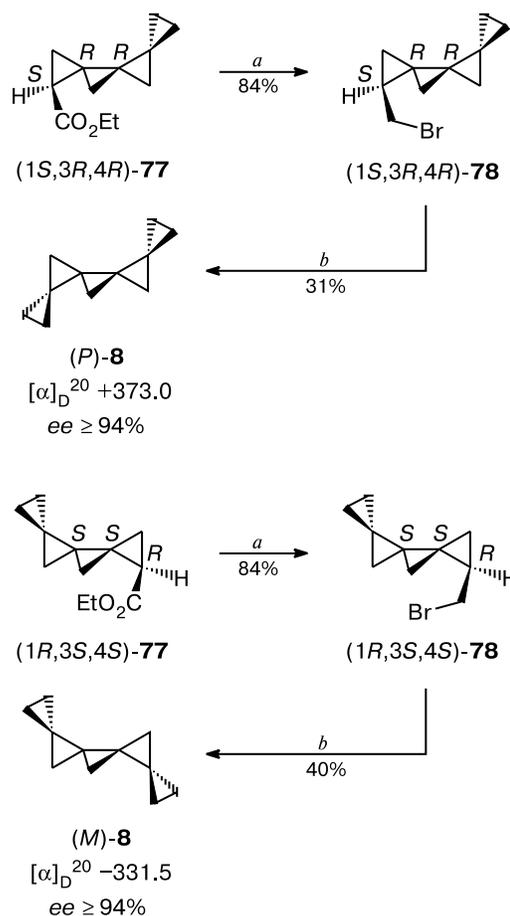
exerts a strong influence even in the long-wavelength region. Indeed, going down in the wavelength, the specific rotation increases to almost 650 at 365 nm. These experimental values were very well reproduced by computations, which showed that the lowest unoccupied molecular orbital (LUMO) has the shape of a double helix. In other words, the skeleton of such a chiral triangulane resembles a helical  $\sigma$ -bond framework, and this leads to the very strong interaction with polarized, *i.e.*, chiral, light. These hydrocarbons may therefore be considered as the  $\sigma$ -analogues of the very well known aromatic helicenes, which consequently should be termed  $\pi$ -helicenes, so that we can call the former ones  $\sigma$ -helicenes. For this reason, we apply the configuration descriptors (*M*) and (*P*) as for helical structures in general.

The computed prediction for the next higher analog of this  $\sigma$ -[4]helicene called for the specific rotation to be about twice that of enantiomerically pure **7**. This certainly intrigued us, and we set out to prepare this analog by cyclopropanation of enantiomerically pure methylene[3]triangulane (*R*)-**74** with ethyl diazoacetate under rhodium tetraacetate catalysis. Since this cyclopropanation goes along with the creation of two new stereogenic centers, a mixture of four different diastereomers was obtained. These diastereomers could not be separated by gas, column, or thin layer chromatography, but — luckily — distillation of this mixture under reduced pressure through a high-performance concentric-tube column led to a significant enrichment with one of the diastereomers in the residue in the distillation flask. This eventually crystallized upon cooling. Good quality crystals were obtained by recrystallization, and an X-ray structure analysis disclosed that this was one of the two diastereomers with the proper configuration for further transformation to the desired enantiomerically pure (*P*)-[5]triangulane (Scheme 19).<sup>36</sup>

Further transformation of enantiomerically pure ester (*1S,3R,4R*)-**77** thus obtained, along the same sequence as used for (*R,S*)-**73**, led to (*P*)-(+)-[5]triangulane (*P*)-**8**, which indeed had a specific rotation of +373 at 589 nm. Enantiomer (*M*)-**8** was also prepared along the same lines from (*S*)-configured methylene[3]triangulane (*S*)-**74**. The product obtained had a specific rotation the absolute value of which was 11% lower than that of (*M*)-**8**, in spite of the fact that the enantiomeric excess, as determined by gas chromatography on a chiral column, was virtually the same. However, this sample turned out to be less chemically pure than that of (*P*)-**8**. Therefore, the experimental value for the latter is certainly more reliable.

Computations predicted that the optical rotations of higher analogues of [5]triangulane would keep growing, but not by the same margin as upon going from, *e.g.*, (*M*)-**7** to (*M*)-**8**, and this prediction therefore should also be tested experimentally. However, this is more easily

Scheme 19



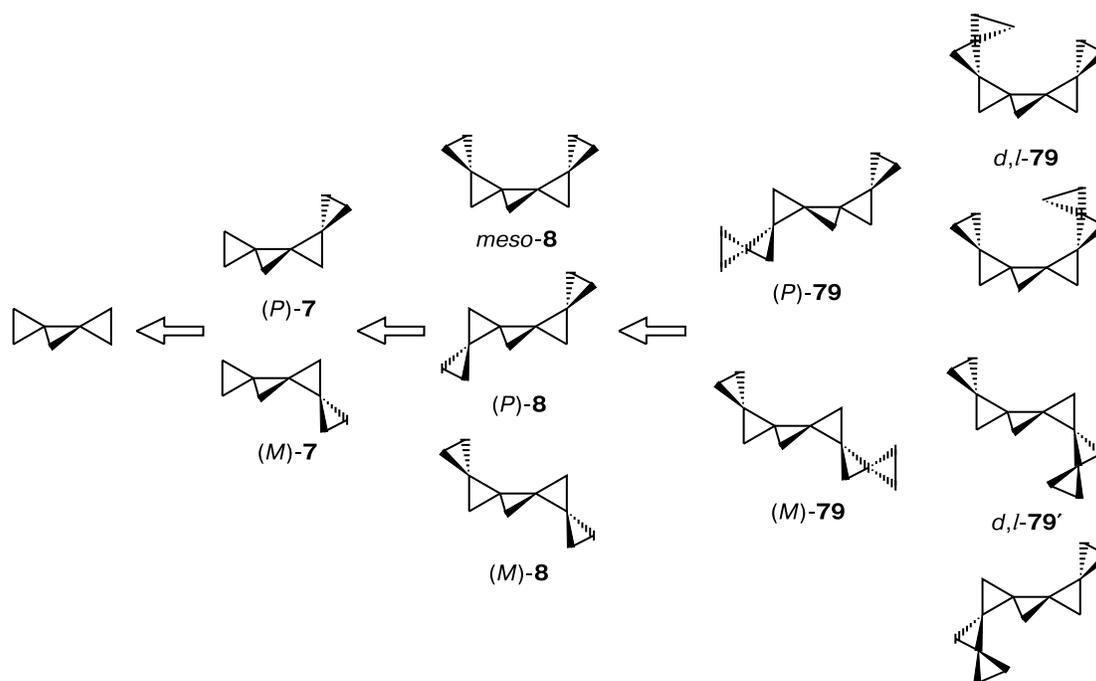
**Reagents and conditions:** *a.* 1) LiAlH<sub>4</sub>, Et<sub>2</sub>O, 2) Ph<sub>3</sub>P·Br<sub>2</sub>, Py; *b.* 1) Bu<sup>t</sup>OK, DMSO, 2) CH<sub>2</sub>N<sub>2</sub>, Pd(OAc)<sub>2</sub>.

said than done: the number of stereoisomers increases exponentially with a growing number of spiroannellated rings in higher [*n*]triangulanes, as has been figured out by Zefirov *et al.* (Scheme 20).<sup>18</sup> The numbers of enantiomeric pairs (*N*<sub>1</sub>) and achiral stereoisomers (*N*<sub>2</sub>) of [*n*]triangulanes<sup>18</sup> are given below.

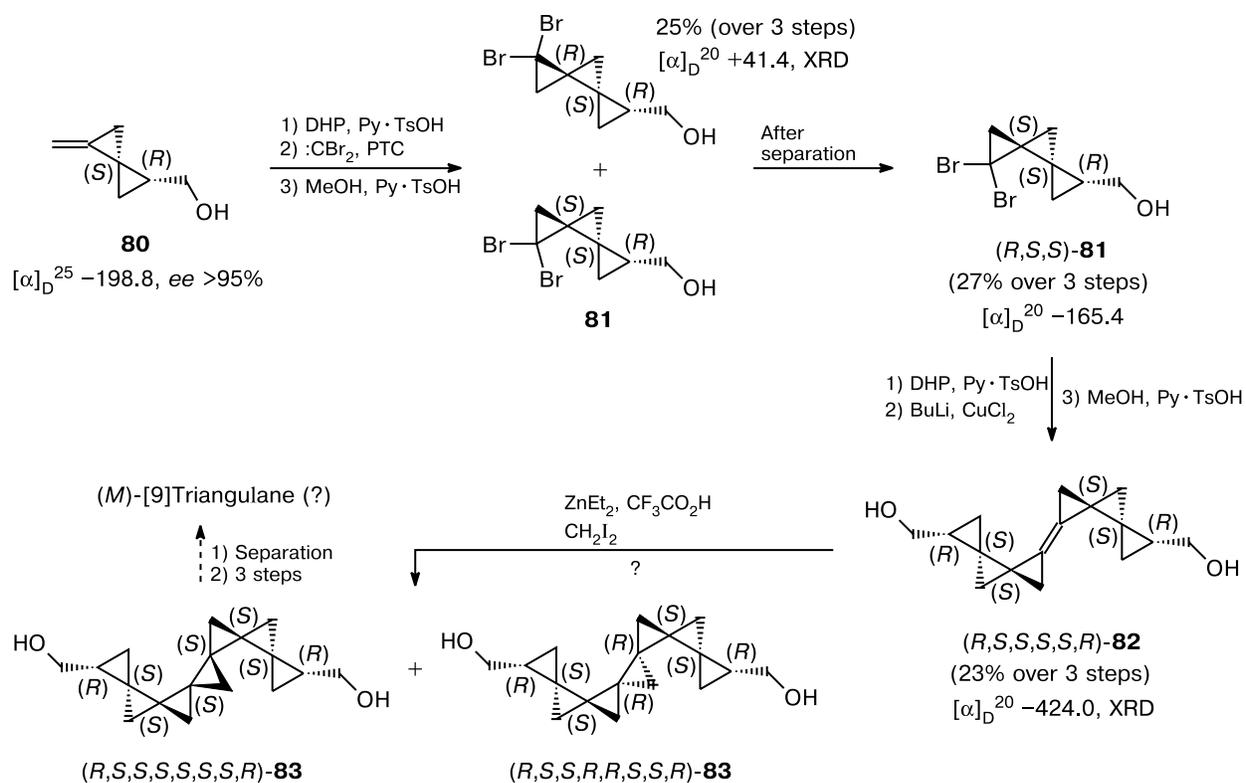
<i>n</i>	2	3	4	5	6	7	8	9	10
<i>N</i> <sub>1</sub>	0	0	1	1	3	4	10	16	36
<i>N</i> <sub>2</sub>	1	1	0	1	0	2	0	4	0

A linear strategy as successfully applied towards the synthesis of (*M*)-**7** and (*M*)-**8** becomes impractical even for the construction of enantiomerically pure (*M*)-[6]triangulane (*M*)-**79** or its enantiomer (*P*)-**79**, because there are two more chiral [6]triangulanes, *d,l*-**79** and *d,l*-**79'**, which would have to be avoided. We have therefore set out to develop a convergent route to enantiomerically pure higher [*n*]triangulanes. This ought to be successful, as 4-methylenespiropentylmethanol (**80**) (Scheme 21) can easily be prepared in large quantities and resolved by li-

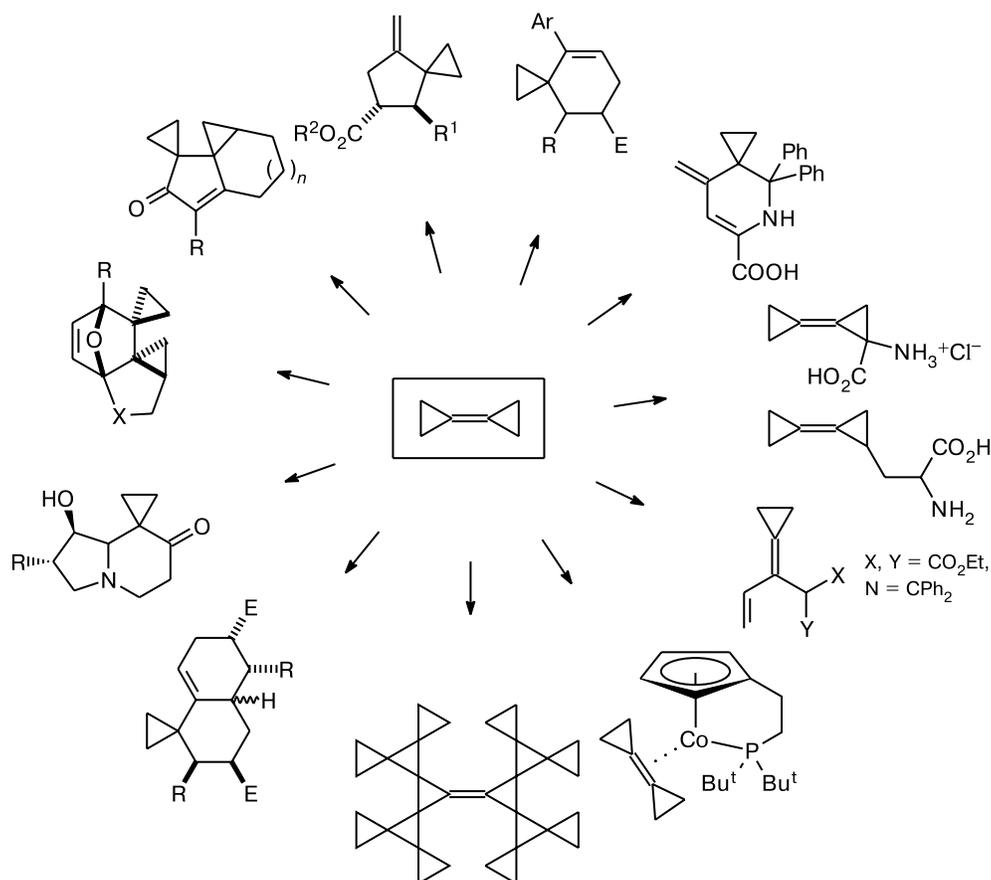
Scheme 20



Scheme 21

DHP is 3,4-dihydro-2*H*-pyran

Scheme 22



pase-catalyzed acetylation with vinyl acetate.<sup>36,37</sup> After protection as a tetrahydropyranyl ether, dibromocarbene addition yields a mixture of two diastereomers which is deprotected to a mixture of dispiro[2.0.2.1]heptyl-methanols **81**. The latter can be separated by column chromatography, enantiomerically pure (*R,S,S*)-**81** is protected again as a tetrahydropyranyl ether, the latter then subjected to the carbenoid dimerization conditions as mentioned above. The product is deprotected again to give a bicyclopropylidenedimethanol derivative as a mixture of two diastereomers which again can be separated by chromatography. Enantiomerically pure (*R,S,S,S,S,R*)-**82** would then be subjected to Simmons—Smith cyclopropanation hoping that it would provide the correct stereoisomer (*R,S,S,S,S,S,R*)-**83** which then would be transformed to (*M*)-[9]triangulane.

The simple C<sub>6</sub>H<sub>8</sub> hydrocarbon bicyclopropylidene (**3**) has thus not only led to the spirocyclopropanated second-generation dendrimer **4**, the third-generation bicyclopropylidene **5** as well as perspirocyclopropanated [3]rotane **2**, but also to the linear helical [4]- and [5]triangulanes in enantiomerically pure forms, and it has inspired work on even higher analogs in this family of σ-[*n*]helicenes.

On top of being a precursor to many of these interesting hydrocarbons, bicyclopropylidene (**3**) has established itself as a versatile multifunctional C<sub>6</sub>-building block from which a multitude of skeletons can be constructed (Scheme 22).<sup>3–6</sup>

This versatility comes along with the high reactivity of its central double bond and the possibility of ring opening of carbocationic, radical, and organometallic intermediates formed upon additions across this double bond. The fact that **3** appears to be a particularly good ligand for various metals enhances its use in transition metal chemistry.

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