DOI: 10.1002/chem.200500472

Preparation and Reactivity of [D_{3d}]-Octahedrane: The Most Stable $(CH)_{12}$ Hydrocarbon

Armin de Meijere,*[a] Chi-Hung Lee,[a] Mikhail A. Kuznetsov,[a] Dmitriy V. Gusev,[b] Sergei I. Kozhushkov,[a] Andrey A. Fokin,*[b, c] and Peter R. Schreiner*[c]

Dedicated to Professor Paul Rademacher on the occasion of his 65th birthday

Abstract: The synthesis of the $(CH)_{12}$ hydrocarbon [D_{3d}]-octahedrane (heptacyclo[6.4.0.0^{2,4}.0^{3,7}.0^{5,12}.0^{6,10}.0^{9,11}]dodecane) **1** and its selective functionalization retaining the hydrocarbon cage is described. The B3LYP/6-311+G* strain energy of **1** is 83.7 kcal mol^{-1} (4.7 kcal mol^{-1} per C–C bond) which is significantly higher than that of the structurally related $(CH)_{16}$ [D_{4d}]-decahedrane **2** (75.4 kcal mol^{-1}; 3.1 kcal mol^{-1} per C–C bond) and $(CH)_{20}$ [I_h]-dodecahedrane **3** (51.5 kcal mol^{-1}; 1.7 kcal mol^{-1} per C–C bond); the heats of formation for **1**–**3** computed according to homodesmotic equations are 52, 35, and 4 kcal mol^{-1}. Catalytic hydrogenation of **1** leads to consecutive opening of the two cyclopropane rings to give C_2-*bisseco*-octahedrane (pentacyclo[6.4.0.0^{2,6}.0^{3,11}.0^{4,9}]dodecane) **16** as the major product. Although **1** is highly strained, its carbon skeleton is kinetically quite stable: Upon heating, **1** does not decompose until above 180 °C. The B3LYP/6-31G* barriers for the S_R2 attack of the *t*BuO$^\bullet$ and $Br_3C^\bullet$ radicals on a carbon atom of one of the cyclopropane fragments ($\Delta G^{\ddagger}_{298}$ = 27–28 kcal mol^{-1}) are higher than those for hydrogen atom abstraction. The latter barriers are virtually identical for the abstraction from the C^1-H and C^2-H positions with the *t*BuO$^\bullet$ radical ($\Delta G^{\ddagger}_{298}$ = 17.4 and 17.9 kcal mol^{-1}, respectively), but significantly different for the reaction at these positions with the $Br_3C^\bullet$ radical ($\Delta G^{\ddagger}_{298}$ = 18.8 and 21.0 kcal mol^{-1}). These computational results agree well with experiments, in which the chlorination of **1** with *tert*-butyl hypochlorite gave a mixture of 1- and 2-chlorooctahedranes (ratio 3:2). The bromination with carbon tetrabromide under phase-transfer catalytic (PTC) conditions (nBu$_4$NBr/NaOH) selectively gave 1-bromooctahedrane in 43 % isolated yield. For comparison, the PTC bromination was also applied to 2,4-dehydroadamantane yielding 54 % 7-bromo-2,4-dehydroadamantane.

Keywords: density functional calculations • halogenation • heats of formation • phase-transfer catalysis • polycycles • small rings

Introduction

Polyhedral hydrocarbon cages, due to their rigidity, unique shape, and esthetic beauty have long attracted considerable attention of both experimentalists and theoreticians.[1,2] Simple functionalized derivatives, particularly of adamantane, display pronounced pharmacological activities.[3] Some cage hydrocarbons, however, cannot easily be functionalized selectively, especially when they are prone to undergo rearrangement due to high ring strain. Hence, only moderately strained cage hydrocarbons (e.g., adamantane) have a rich chemistry and are used for a number of practical applications.[2,4] This is in line with the ease of selective adamantane functionalizations under ionic (bromination, nitroxylation) and free-radical (chlorination, hydroxylation) conditions. Herein we present and discuss the preparation, structural and energetic features as well as the reactivity of [D_{3d}]-octa-

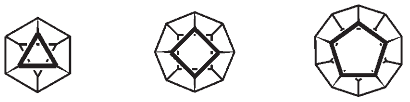
---

[a] Prof. Dr. A. de Meijere, Dr. C.-H. Lee, Dr. M. A. Kuznetsov,
Dr. S. I. Kozhushkov
Institut für Organische und Biomolekulare Chemie
Georg-August-Universität Göttingen
Tammannstrasse 2, 37077 Göttingen (Germany)
Fax: (+49) 551-399-475
E-mail: Armin.deMeijere@chemie.uni-goettingen.de

[b] Dr. D. V. Gusev, Prof. Dr. A. A. Fokin
Department of Organic Chemistry
Kiev Polytechnic Institute, pr. Pobedy 37
03056 Kiev (Ukraine)
E-mail: aaf@xtf.ntu-kpi.kiev.ua

[c] Prof. Dr. A. A. Fokin, Prof. Dr. P. R. Schreiner
Institut für Organische Chemie
Justus-Liebig-Universität
Heinrich-Buff-Ring 58, 35392 Giessen (Germany)
Fax: (+49) 641-993-4309
E-mail: prs@org.chemie.uni-giessen.de

hedrane (**1**), which has been suggested[5] to be the most stable of all $(CH)_{12}$ hydrocarbons.[6] For comparison, the structurally related higher $(CH)_n$ polyhedranes, that is [D_{4d}]-decahedrane (**2**, $n=16$) and [I_h]-dodecahedrane (**3**, $n=20$) (Figure 1) will also be evaluated.



1 $C_{12}H_{12}$ **2** $C_{16}H_{16}$ **3** $C_{20}H_{20}$

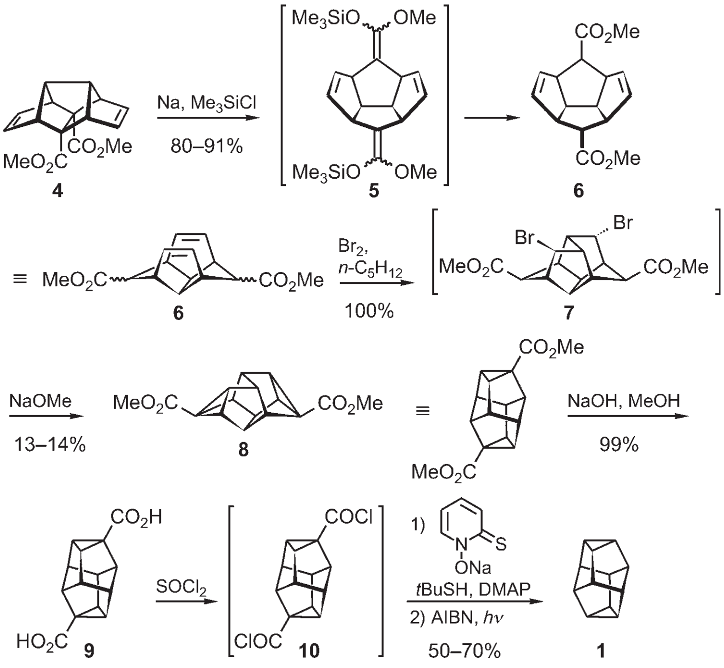
Figure 1. [D_{3d}]-Octahedrane **1** and selected structurally related higher $(CH)_n$ ($n=16$ and 20) polyhedranes.

Results and Discussion

Preparation of [D_{3d}]-octahedrane (1):[7] The literature procedure[8] for the preparation of the precursor **4** of the dimethyl octahedrane-2,10-dicarboxylate (**8**) (Scheme 1) was improved by using a sodium cyclopentadienide solution prepared with metallic sodium[9] instead of sodium hydride (overall yield 12–14%). Reduction of **4** with sodium in toluene in the presence of chlorotrimethylsilane according to the published procedure[10] yielded a mixture of *endo*,*endo*-, *endo*,*exo*-, and *exo*,*exo*-stereoisomers of diester **6** in a 75:13:2 ratio (80–91% yield). Base-catalyzed isomerization in the presence of sodium methoxide[10] gave a mixture enriched with the *exo*,*exo*-diastereomer (ratio 1:21:67). The addition of bromine to **6** provided a mixture of dibromodiesters including **7** which, upon treatment with sodium methoxide, underwent twofold γ-dehydrobromination to yield **8** (13–14%). When the crude product after reduction of **4**, containing mostly the *endo*,*endo*-diastereomer of diester **6** was used, the yield of **8** was only 7–8%. A number of other brominating agents (e.g., dioxane dibromide and pyridinium hydrobromide perbromide) led to tarry product mixtures. Hydrolysis of diester **8** with methanolic-aqueous sodium hydroxide gave diacid **9**, which is almost insoluble in common organic solvents. Decarboxylation[11] of **9** via the diacid dichloride **10** and the Barton ester generated from **10** by reaction with the sodium salt of *N*-hydroxypyridine-2-thione gave octahedrane **1** in 50–70% yield.

Structures and energies: The structures of [D_{3d}]-octahedrane (**1**), the next higher polyhedranes [D_{4d}]-decahedrane (**2**)[12–14] as well as [I_h]-dodecahedrane (**3**),[12] were computed at different levels of theory (Figure 2, Table 1). The bond lengths computed at the MP2/6-31G* level agree particularly well with the available X-ray crystal data (in parentheses) for **1**[7] and **3**.[15]

The strain energies of polyhedranes **1**–**3** were evaluated according to the homodesmotic Equations (1)–(3) at B3LYP/6-311+G*. In contrast to dodecahedrane **3**, which displays nearly an idealized tetrahedral geometry around all carbon atoms,[12,16] and which is strained mainly due to nonbonding interactions [1.7 kcal mol^{-1} per C–C bond according to Eq. (3)], the central belts of **1** and **2** are severely distorted: The CCC angle in the six-membered ring of **1** is 101.0°, and in the eight-membered ring of **2** it is 106.9°. This, in addition to the strain arising from the presence of the two small rings in each case, increases the strain energies per C–C bond of **1** and **2** to 4.7 and 3.1 kcal mol^{-1}, respectively. The DFT and MP2/6-31G* (54.0 kcal mol^{-1}) calculated strain energies of **3** are slightly lower than previous estimates from isodesmotic equations[17] and bond force computations (65.4 kcal mol^{-1}),[18] but somewhat higher than most recent HF/6-31G* calculations according to Equation (3) (43.7 kcal mol^{-1}).[19] At the uncorrelated HF/6-31G* level the strain energy of **2** is similarly underestimated[19] [71.2 kcal mol^{-1} according to Eq. (2)].



Scheme 1. Preparation of [D_{3d}]-octahedrane **1**.

Table 1. B3LYP/6-311+G* energies of the selected computed species.

Structure	Symmetry group	$-E$ [au] B3LYP /6-311+G*	ZPVE [kcal mol^{-1}] B3LYP /6-311+G*	$-\Delta H^{298}$ [au] B3LYP /6-311+G*
C_2H_6	D_{3d}	79.84841	46.83	79.76935
C_3H_8	C_{2v}	119.17050	64.83	119.06172
i-C_4H_{10}	C_{3v}	158.49339	82.47	158.35534
diamantane (**11**)	D_{3d}	545.68177	197.78	545.35678
adamantane (**12**)	T_d	390.80460	153.17	390.55275
$C_{12}H_{12}$ (**1**)	D_{3d}	464.51641	130.28	464.30183
$C_{16}H_{16}$ (**2**)	D_{4d}	619.41292	177.21	619.12247
$C_{20}H_{20}$ (**3**)	I_h	774.33430	224.51	773.96680

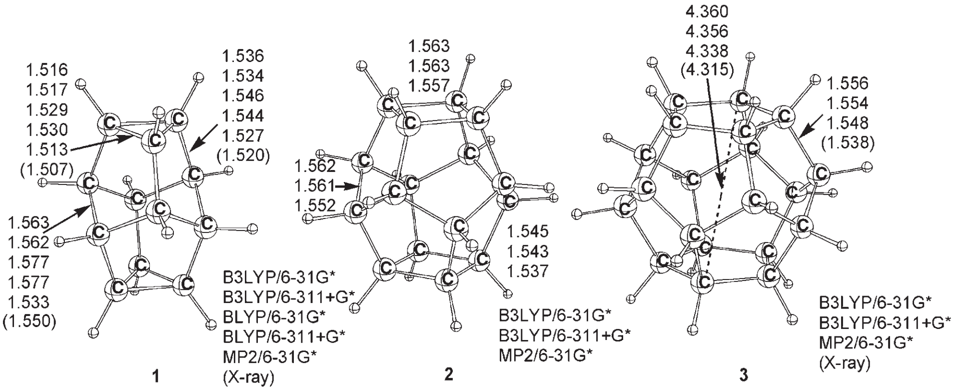


Figure 2. Optimized geometries of [D_{3d}]-octahedrane (**1**), [D_{4d}]-decahedrane (**2**), and [I_h]-dodecahedrane (**3**) at different levels of theory [bond lengths in Å, experimental (X-ray) bond lengths in parentheses].

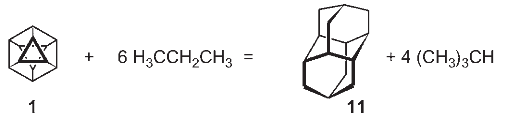
$$\mathbf{1} + 18\,CH_3CH_3 \;=\; 12\,(CH_3)_3CH \quad \Delta E = 83.7\,\mathrm{kcal\,mol^{-1}} \qquad (1)$$

$$\mathbf{2} + 24\,CH_3CH_3 \;=\; 16\,(CH_3)_3CH \quad \Delta E = 75.4\,\mathrm{kcal\,mol^{-1}} \qquad (2)$$

$$\mathbf{3} + 30\,CH_3CH_3 \;=\; 20\,(CH_3)_3CH \quad \Delta E = 51.5\,\mathrm{kcal\,mol^{-1}} \qquad (3)$$

Several homodesmotic equations were used to calculate the experimentally unknown enthalpies of formation of polyhedranes **1**–**3** employing B3LYP/6-311+G* reaction enthalpies and experimental heats of formation[20] of various reference hydrocarbons. These values coincide well for hydrocarbon **1** [$\Delta H_f^{298} = +51.0$, $+52.5$, and $+51.8$ kcal mol^{-1} according to Eqs. (1), (4), and (5), respectively], as well as for **2** [$\Delta H_f^{298} = +34.4$ and $+35.5$ kcal mol^{-1} from Eqs. (2), and (6)].

Previous calculations of the enthalpy of formation of **3** by various approaches[17,21,22] varied from −8.4 to 62.3 kcal mol^{-1}. Current B3LYP/6-311+G* computations give $\Delta H_f^{298} = +3.0$ and $+4.4$ kcal mol^{-1} according to Equations (3) and (7), respectively; the MP2/6-31G* energy values are virtually identical to those at DFT. Thus, accurate DFT and MP2 computations decrease the computed enthalpy of formation of **3** to 3–4 kcal mol^{-1}; earlier HF/6-31G* and MP2/6-31G*//HF/6-31G* values range from 13 to 19 kcal mol^{-1}.[22]



(4)

(5)

(6)

(7)

Reactivities of [D_{3d}]-octahedrane (1): The hydrocarbon **1** turned out to be rather stable thermally. Thus, no changes were observed in the ^{1}H NMR spectrum after heating a solution of **1** in [D$_6$]DMSO (1 mg of **1** in 0.5 mL [D$_6$]DMSO, $\delta = 1.61$ and 2.98 ppm) for 13 h at 120 as well as at 140 °C. However, upon heating this sample at 170 °C, rearrangement did occur with 84 % conversion after 13 h. Three unidentified products in the ratio 1:1:3.3 were formed, each containing a double bond. According to differential scanning calorimetry (DSC) measurements, however, the hydrocarbon melts at 110 °C and shows another first order transition at 160 °C, but starts to decompose only above 180 °C. Thus, the observed rearrangement in [D$_6$]DMSO at 170 °C must have been enhanced by the solvent.

The hydrogenolytic opening of a single bond in **1** can lead to the three isomeric *seco*-octahedranes **13**–**15**; according to B3LYP/6-311+G* calculations, isomer **13** (Figure 3) is the least strained one. It is not surprising that addition of one equivalent of hydrogen to **1** is expected to be quite selective for the opening of one of the three-membered rings. Hydrogenolytic opening of both three-membered rings would give **16** and **17**, which are closer in energy than **13**–**15**, but still 11.3 kcal mol^{-1} apart.

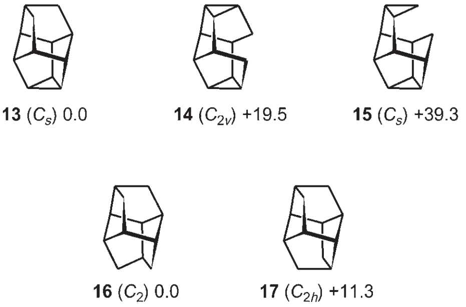
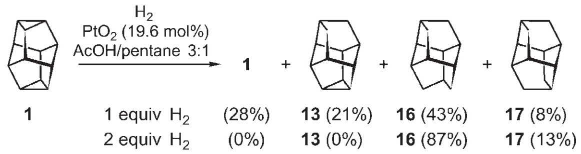


Figure 3. Monoseco- (**13**–**15**) and selected bisseco-[D_{3h}]-octahedranes (**16** and **17**) (relative B3LYP/6-311+G* energies in kcal mol^{-1}).

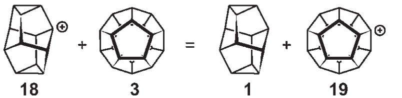
Experimentally, catalytic hydrogenation of **1** in acetic acid/pentane 3:1 over platinum oxide[23,24] after consumption of one equivalent of hydrogen gave a mixture of 21 % monoseco- **13** as well as both isomeric bisseco-[D_{3h}]-octahedranes **16** (43 %) and **17** (8 %) along with unchanged starting material **1** (28 %). This indicates that hydrogenolytic opening of the remaining cyclopropane ring in the monoseco-hydrocarbon **13** occurs even more rapidly than that of the first one in **1** (Scheme 2). As predicted by the computations, the C_2-symmetrical bisseco derivative **16** is formed predominantly. After consumption of two equivalents of hydrogen, the bisseco-[D_{3h}]-octahedranes **16** and **17** were obtained in quantitative yield in a ratio of 6.7:1. The structural assignments rest on a comparison of the ^{13}C NMR spectra of both reaction mixtures, taking the symmetries of hydrocarbons **13**, **16**, **17** into account. Thus, since **13** possesses a plane of symmetry, eight signals should be observed in its ^{13}C NMR spectrum (1 signal 2 × CH$_2$, 3 signals 2 × CH and 4 signals 1 × CH each). The bisseco-derivative **17** has C_{2h} symmetry, and accordingly only four signals are observed in its ^{13}C NMR spectrum (1 signal 4 × CH$_2$, 2 signals 2 × CH each and 1 signal 4 × CH). The isomer **16** is C_2-symmetric only, and its ^{13}C NMR spectrum thus shows six signals of equal intensities. Thus, in this case the thermodynamically most stable isomer **16** is formed upon hydrogenolytic opening of both three-membered rings in **1**. This is remarkable, since hydrogenolysis of oligocyclic hydrocarbons with more than one cyclopropane moiety does not necessarily occur with thermodynamic control, as had previously been hypothesized,[25] but may be governed by the mode of adsorption on the catalyst surface.[26]



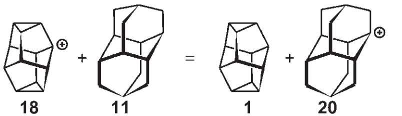
Scheme 2. Hydrogenation of [D_{3h}]-octahedrane **1** under PtO$_2$ catalysis with one and two equivalents of hydrogen.

Direct functionalizations of several cage hydrocarbons, especially adamantane (**12**), with electrophilic (bromination,[27] nitroxylation[28]) or radical (halogenation,[29] oxygenation[30]) reagents have been studied. Bromination of the structurally related hydrocarbon diamantane **11** occurs at the "belt" C-H position under mild conditions.[31] Due to the high stability of the planarized dodecahedryl cation **19**,[32] the electrophilic C-H substitutions of dodecahedrane (**3**) occur with similar ease and give monosubstituted derivatives in high yields.[33] The cage of [D_{3d}]-octahedrane (**1**) is much more rigid and the "belt" position of the 1-octahedryl cation **18** is not able to planarize. This places **18** 20.1 kcal mol^{-1} above[34] the dodecahedryl (**19**) and 26.2 kcal mol^{-1} above the 1-diamantyl (**20**) cations [Eqs. (8) and (9), B3LYP/6-311+G*]. Due to significantly higher flexibility of the cage, the decahedryl cation **21** is 11.8 kcal mol^{-1} more stable than **18** [Eq. (10)]. Thus, any C-H substitution of the octahedrane cage is unlikely to occur with electrophilic reagents; the alternative attack of the electrophile at the cyclopropane moiety with concomitant ring opening is more likely.[35] On the other hand, the destabilization of the 1-octahedryl radical **22** is less pronounced as the homodesmotic reactions according to Equations (11) and (12) are significantly less exergonic relative to Equations (8) and (9). This makes the abstraction of hydrogen from the octahedrane cage and its substitution with radical reagents feasible.

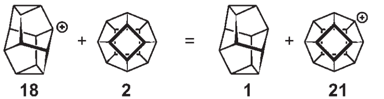
Free-radical C-H substitutions are well documented in hydrocarbon chemistry.[29] For the case of [D_{3d}]-octahedrane (**1**), two different types of abstracting species, namely the oxygen- and carbon-centered radicals *t*BuO$^\bullet$ and Br$_3$C$^\bullet$ that have proven to be useful for metal-free alkane functionalizations, were chosen.[30] Both C-H substitution paths were computed because the 1-octahedryl radical **22** is only 3.5 kcal mol^{-1} more stable than 2-octahedryl isomer **25** (Figure 4); the S$_R$2 attack on the cyclopropane ring of **1** was also considered (Figure 4, ΔG^{298}, B3LYP/6-31G*; Table 2). The cyclopropane ring openings with *t*BuO$^\bullet$ (**TS1**) and Br$_3$C$^\bullet$ (**TS2**) to give **26** and **27**, respectively, are favored thermodynamically (ΔG^{298} = −8.1 and −9.5 kcal mol^{-1}), but require higher activation energies than hydrogen abstractions by the *t*BuO$^\bullet$ radical with 17.4 and 17.9 kcal mol^{-1} ($\Delta\Delta G^{\ddagger}_{298}$ = 0.5 kcal mol^{-1} for **TS3** vs **TS4**). Whereas radical C-H abstraction by *t*BuO$^\bullet$ would be unselective, the attack by Br$_3$C$^\bullet$ should allow for discrimination between the C^1-H and C^2-H positions of **1** ($\Delta\Delta G^{\ddagger}_{298}$ = 2.2 kcal mol^{-1} for **TS5** vs **TS6**). The



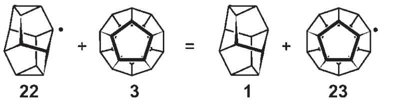
ΔE = −20.1 kcal mol^{-1} (8)



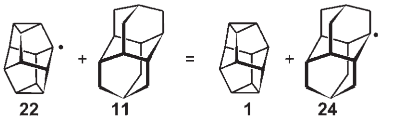
ΔE = −26.2 kcal mol^{-1} (9)



ΔE = −11.8 kcal mol^{-1} (10)



ΔE = −8.3 kcal mol^{-1} (11)



ΔE = −6.2 kcal mol^{-1} (12)

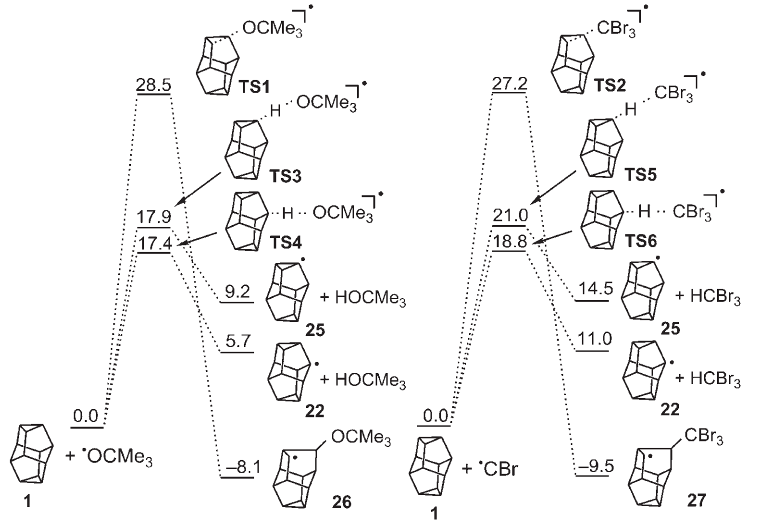


Figure 4. B3LYP/6-31G* computed paths for the reactions of [D_{3d}]-octahedrane **1** with tBuO$^{\bullet}$ and Br$_3$C$^{\bullet}$ radicals (relative B3LYP/6-31G* ΔG^{298} in kcal mol^{-1}).

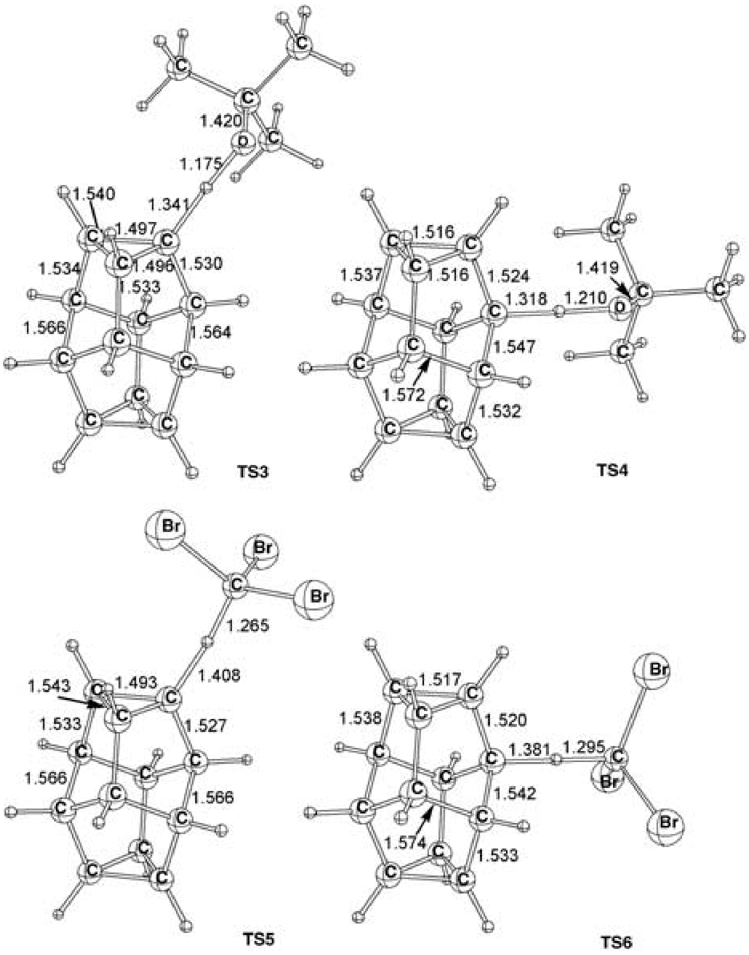


Figure 5. B3LYP/6-31G* optimized geometries of **TS3**–**TS6** (bond lengths in Å).

differences in the selectivities of the tBuO$^{\bullet}$ and Br$_3$C$^{\bullet}$ arise from the relative positions of **TS3**–**TS6** along the reaction coordinate. The crucial C···H distances (Figure 5) in the early **TS3** and **TS4** are shorter (1.34 and 1.32 Å) than in **TS5** and **TS6** (1.41 and 1.38 Å). The latter two resemble the differences in the stabilities of the octahedryl radicals **22** and **25** closely. Thus, computations reveal that the selectivities in the radical substitutions of the [D_{3d}]-octahedrane **1** are higher for carbon-centered than for oxygen-centered radicals.[29,30,36]

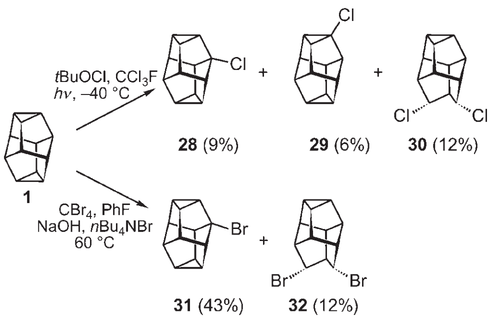
The computational results were probed experimentally by photochlorination of **1** with *tert*-butyl hypochlorite[37] and by bromination with carbon tetrabromide under PTC conditions[38] as previously established for hydrocarbon C-H functionalizations[36] involving the Br$_3$C$^{\bullet}$ radical (Scheme 3).[39] Irradiation of *tert*-butyl hypochlorite in the presence of **1** in CCl$_3$F gave the 1- (**28**) and 2-octahedryl chlorides **29** in low yields (9 and 6 %, respectively), along with the dichloride **30** (12 %) arising from the C–C bond cleavage of one of the cyclopropane rings.

In contrast to the photochlorination with *tert*-butyl hypochlorite, the PTC bromination of **1** with carbon tetrabromide gave the single C-H substitution product 1-bromooctahedrane **31** in 43 % isolated yield along with only a small amount (12 %) of the dibromide **32** arising from an addition of bromine across one of the cyclopropane single bonds. This is in complete accord with the computational results above (Figure 4).

The PTC halogenation once again demonstrates its high potential for the effective C-H substitution of strained hydrocarbon cages, as in, for example, cubane[36] with a high degree of cage conservation. [D_{3d}]-Octahedrane (**1**) is a more difficult case than cubane because cage opening would be highly favorable, in contrast to cubane in which breaking just one C–C bond causes only little structural changes.[40] To emphasize the power of this method further, the PTC pro-

Table 2. B3LYP/6-31G* energies of the computed species.

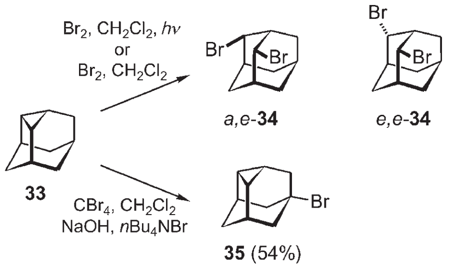
Structure	Symmetry group	N_{im}	$-E$ [au] B3LYP /6-31G*	ZPVE [kcal mol^{-1}] B3LYP /6-31G*	$-\Delta G^{298}$ [au] B3LYP /6-31G*
TS1	C_1	1	697.40455	208.57	697.11328
TS2	C_1	1	8217.55067	134.18	8217.38017
TS3	C_1	1	697.41466	205.36	697.13010
TS4	C_1	1	697.41587	205.42	697.13095
TS5	C_s	1	8217.55313	131.15	8217.39000
TS6	C_1	1	8217.55721	131.19	8217.39349
octahedrane (**1**)	D_{3d}	0	464.42639	131.18	464.24608
octahedr-1-yl radical (**22**)	C_s	0	463.75048	122.81	463.58584
octahedr-2-yl radical (**25**)	C_s	0	463.74512	122.99	463.58020
26	C_1	0	697.46713	210.62	697.17160
27	C_1	0	8217.61334	135.85	8217.43869
$Br_3C^{\bullet}$	C_{3v}	0	7753.15065	3.38	7753.17739
$Me_3CO^{\bullet}$	C_s	0	233.00617	77.25	232.91261
$CHBr_3$	C_{3v}	0	7753.80644	11.24	7753.82003
Me_3COH	C_s	0	233.67096	85.45	233.56379



Scheme 3. Halogenations of **1** with *t*BuOCl under irradiation and with CBr_4 under PTC conditions.

tocol was applied to the bromination of 2,4-dehydroadamantane[41] (**33**), which had served as a model for strained hydrocarbon functionalizations in a number of previous studies.[42]

Previous brominations of **33** with Br_2 under radical (photobromination) and ionic conditions exclusively gave the ring-opened diastereomeric dibromides *a*,*e*- and *e*,*e*-**34** in a ratio of 1.4 to 2.[43] With carbon tetrabromide under PTC conditions (Scheme 4), only small amounts (<10%) of dibromides **34** were formed, and 7-bromo-2,4-dehydroadamantane (**35**) was isolated in 54% yield. Thus, the PTC bromination protocol is especially valuable for C-H substitutions of strained hydrocarbons.



Scheme 4. Brominations of 2,4-dehydroadamantane (**33**) with Br_2 (with or without irradiation) and with CBr_4 under PTC conditions.

Due to the instability of the 1-octahedryl cation, 1-halo-**28** as well as **31** and 2-halooctahedrane **29**, resist S_N1 solvolysis even under drastic reaction conditions. Heating **31** in a methanol/water mixture in the presence of potassium carbonate in a sealed tube at 160 °C for 48 h gave only products of CH_3OH addition to the cyclopropane C–C bond leaving the C–Hal bond untouched.

Conclusion

Despite being the most stable isomer among the $(CH)_{12}$ hydrocarbons, [D_{3d}]-octahedrane (**1**) is more strained ($E_{str} = 83.7$ kcal mol^{-1}) and has a higher enthalpy of formation ($\Delta H_f^{298} = +52$ kcal mol^{-1}; 4.7 kcal mol^{-1} per one C–C bond) than the structurally related polyhedranes $(CH)_{16}$ [D_{4d}]-decahedrane **2** ($\Delta H_f^{298} = +35$ kcal mol^{-1}; 3.1 kcal mol^{-1} per C–C) and $(CH)_{20}$ [I_h]-dodecahedrane **3** ($\Delta H_f^{298} = +4$ kcal mol^{-1}; 1.7 kcal mol^{-1} per C–C). The B3LYP/6-311+G* enthalpy of formation of **3** ($\Delta H_f^{298} = 3$–4 kcal mol^{-1}) substantially differs from previous estimates obtained at lower computational levels (13–19 kcal mol^{-1} at HF/6-31G* and MP2/6-31G*//HF/6-31G*).

Traditional methods for the functionalization of cage hydrocarbons in the case of **1** mostly lead to ring-opened products. Owing to the instability of the 1-octahedryl cation, the C-H substitution of **1** with electrophilic reagents is severely hampered. The photochlorination of **1** with *tert*-butyl hypochlorite does give low yields of C-H substitution, but also cyclopropane addition products. The functionalization is possible with the more selective carbon-centered radical $Br_3C^{\bullet}$ generated under phase-transfer catalytic conditions. This procedure gave 1-bromooctahedrane (**31**) in 45% isolated yield. The PTC protocol again proves to be generally useful for the C-H functionalization of strained cage hydrocarbons. The analogous bromination of 2,4-dehydroadamantane (**33**) yielded 54% 7-bromo-2,4-dehydroadamantane (**35**).

Experimental Section

General methods: NMR: Varian VXR-300 and Bruker spectrometers at 300 and 250 MHz (^{1}H NMR) and 75 and 62.9 MHz (^{13}C NMR) in $CDCl_3$. The chemical shifts are given in ppm; the internal standard was tetramethylsilane. The GC/MS analyses were performed on an HP5890 with an H5971 A detector (HP GC-MS capillary column 50 m × 0.2 mm, Ultra1, silicone, 80–250 °C). All compounds showed adequate IR and DEPT ^{13}C NMR spectra.

All solvents, especially THF, must be strictly anhydrous and free of oxygen. Even a trace of oxygen in THF led to an intensive tar formation in the course of the reaction and hampers the isolation (foaming, formation of stable emulsions) and purification of the target compounds. As a result the yields were significantly lowered.

Dimethyl 3,3a,3b,4,6a,7a-hexahydro-3,4,7-metheno-7*H*-cyclopenta[*a*]pentalene-7,8-dicarboxylate (4) (as adapted from ref. [8]): In a 2 L three-necked flask, fitted with a highly efficient mechanical stirrer (Hershberg type), a reflux condenser with a bubbler, and a gas inlet, were placed anhydrous toluene (250 mL), and under a sweep of nitrogen sodium (40.8 g, 1.77 mol) was added. The mixture was heated to boiling, and the sodium was finely dispersed by rapid stirring. Stirring was stopped after 1–2 min, and the mixture allowed to cool to ambient temperature under nitrogen. The bulk of the toluene was removed with a syringe, the residue was washed twice with anhydrous THF (100 mL each, with a syringe), then anhydrous THF (850 mL) was added. The stirrer was exchanged for one with a regular Teflon blade and the reaction flask was equipped with a 250 mL pressure-equalizing jacketed addition funnel. The sodium dispersion in THF was cooled in an ice-bath and the jacket of the addition funnel was cooled with dry ice/acetone. From the addition funnel was added dropwise freshly distilled cyclopentadiene (117 g, 1.77 mol) at such a rate as to avoid loss of cyclopentadiene through the reflux condenser, and stirring was continued for about 1 h in the ice-bath and for an additional 1 to 2 h at RT, after which an almost clear, colorless solution of sodium cyclopentadienide in THF had formed.

The jacketed addition funnel was removed, and $CuBr{\cdot}Me_2S$ complex (0.64 g, 3.1 mmol) was added. A 500 mL pressure-equalizing addition funnel was attached to the flask, and a solution of sublimed iodine (224.8 g, 0.886 mol) in anhydrous deoxygenated THF (215 mL) was added dropwise with stirring to the sodium cyclopentadienide solution under cooling in a dry ice-acetone bath within 1.5–2 h. The solution was stirred for an additional 15–20 min, dimethyl acetylenedicarboxylate (140 g, 0.985 mol) was added dropwise within 10–15 min, and stirring was continued for 30 min. At this point the reaction mixture may be left in the cooling bath overnight.

The cooling bath was removed, and stirring was maintained for 4–5 h. A precipitate of sodium iodide formed, and a gentle exotherm was observed. The reaction mixture was filtered through a pad of Celite (~1 cm thick), and the solids were washed repeatedly with anhydrous THF (total of ~0.7 L). The combined dark brown filtrates were concentrated under reduced pressure below 30°C on a rotary evaporator. The residue was taken up in diethyl ether (0.7 L), the mixture was kept in motion on the rotary evaporator for 15 min, again filtered through Celite and concentrated below 30°C to yield a dark red-brown oil. The oil was dissolved in methanol (850 mL), and this solution was placed in a three-necked 2 L flask equipped with a magnetic stirrer, internal thermometer, a 250 mL addition funnel with gas inlet, and a bubbler. The solution was cooled to −5°C in an ice-salt bath. A solution of KOH (95 g) in water (170 mL) was added dropwise at such a rate as to keep the temperature below 10°C. The reaction mixture was stirred at 0°C for an additional 2 h and at RT for 1 h prior to the addition of glacial acetic acid (43 mL). The resulting neutral dark solution was filtered through Celite. Concentration of the filtrate below 35°C under reduced pressure afforded a dark liquid (ca. 400 mL). This rather time-consuming step (at least 3 h) should be carried out with great care to avoid formation of a stable emulsion in the subsequent extraction.

The liquid was diluted with water (900 mL) and extracted with distilled pentane (8×250 mL). The combined extracts were washed with sat. aqueous $Na_2S_2O_3$ solution (350 mL) and dried over $MgSO_4$ overnight. The pentane was evaporated under reduced pressure, and the tan, somewhat tarry solid residue (34.6 g, 14.3 %), was washed with pentane(50 mL) to leave behind slightly yellow transparent crystals (31.0 g, 12.8 %; purity >99 % by GC, 160 to 250°C, 15°C$\,min^{-1}$, t_r = 2.8–2.9 min) of **4**; from the pentane solution an additional amount of **4** (3.6 g, 1.5 %) was obtained as a yellow oil with crystalline inclusions (~80 % purity) which could be purified by column chromatography on silica. The spectroscopic data were as reported in ref. [8].

Dimethyl 2a,3,3a,5a,6,6a,6b,6c-octahydrodicyclopenta[*cd*,*gh*]pentalene-3,6-dicarboxylate (6): In a 2 L three-necked flask, fitted with a powerful turbo stirrer, a reflux condenser with a bubbler, and a gas inlet, were placed anhydrous toluene (1.35 L), and under a sweep of nitrogen sodium (51.0 g, 2.22 mol). The mixture was heated to boiling, and the sodium finely dispersed by rapid stirring. Stirring was stopped after 1–2 min, and the mixture allowed to cool to ambient temperature under nitrogen. The turbo stirrer was replaced by an ordinary mechanical stirrer, and the reaction flask equipped with a 250 mL pressure-equalizing addition funnel. The sodium suspension was heated at 70–80°C, and Me_3SiCl (300 mL, 257 g, 2.36 mol) was added with a syringe. A solution of diester **4** (15.42 g, 56.6 mmol) in anhydrous toluene (150 mL) was added dropwise. After having been stirred under reflux for 14 h, the mixture was filtered through Celite.

CAUTION! *Finely dispersed sodium on a filter is pyrophoric. It must* ***immediately*** *be transferred to a suitable flask and destroyed by cautious addition of ethanol and subsequently water.*

The filtrate was concentrated to ~300 mL on a rotary evaporator (bath temperature <70°C) and then added dropwise with stirring under nitrogen to anhydrous methanol (1.5 L). After dilution of the methanol solution with water (7.5 L) the resulting emulsion was extracted with distilled pentane (3×1.5 L). The pentane solution was washed with water (3×3 L) and dried overnight ($MgSO_4$). The pentane was removed in vacuo to give a yellow oil (14.7 g), which (GC, 160 to 250°C, 15°C$\,min^{-1}$) consisted of 75 % *endo*,*endo*-, 13 % *endo*,*exo*-, 2 % *exo*,*exo*-diester **6** (t_r = 4.35, 3.98, and 3.81 min, respectively), and about 10 % side products. The total yield of all three stereoisomers of **6** was 85 %. This mixture can be separated by column chromatography on silica gel, eluting first with petroleum ether (PE), then PE/Et_2O 3:1. On the average, the yield of **6** was 80–91 %. The crude product contained 60–70 % *endo*,*endo*-, 10–23 % *endo*,*exo*-, and 1–5 % *exo*,*exo*-diester **6**. Very often a spontaneous crystallization of this oil at room temperature was observed. The spectroscopic data were as reported in ref. [10].

***endo*,*endo*- → *exo*,*exo*-Isomerization of diester 6**: The crude mixture of stereoisomers **6** obtained in the previous step (14.7 g, ~48 mmol) was dissolved in anhydrous MeOH (500 mL) and stirred with a solution of sodium (2.46 g, 0.107 mol) in thoroughly degassed anhydrous MeOH-(200 mL) for 5.5 d under nitrogen. After the addition of sat. aqueous ammonium chloride (250 mL), the reaction mixture was diluted with water (7 L) and extracted with Et_2O (3×2.4 L). The combined organic extracts were washed with water (3×5 L), brine (5 L) and dried ($MgSO_4$) overnight. Removal of the solvent yielded a yellow oil (11.7 g, 80 %), which (GC, 160 to 250°C, 15°C$\,min^{-1}$) consisted of 67 % *exo*,*exo*-, 21 % *endo*,*exo*-, 1 % *endo*,*endo*-diester **6** and ~11 % impurities.

ATTENTION! This product turned out to be rather sensitive towards oxygen, and after 10–20 min in the air at RT a significant amount of a dark brown tar formed, which was insoluble in pentane (the *endo*,*endo*-isomer of **6** predominating before isomerization is somewhat more stable). The mixture enriched in *exo*,*exo*-**6** can be stored in a refrigerator (upon which slow crystallization occurs) or as a solution.

In several experiments, the average yield at this stage was 80–90 %. The crude product contained 65–75 % *exo*,*exo*-, 18–25 % *endo*,*exo*-, and 1–3 % *endo*,*endo*-diester **6**. With a catalytic amount[10] of sodium methoxide (about 0.1 mol for 1 mol of diester) the isomerization occurred very slowly and took longer than one month at room temperature. Attempts to accelerate the isomerization at somewhat elevated temperature (45–55°C) led to very dark reaction mixtures and loss of product (yields 15–50 %).

Dimethyl [D_{3d}]-octahedrane-2,10-dicarboxylate (8): Into a 1 L three-necked flask, fitted with a magnetic stirring bar, an immersing thermometer, a 100 mL pressure-equalizing addition funnel with a gas inlet, and with a bubbler, was placed a solution of crude *exo*,*exo*-diester **6** (7.03 g, 25.6 mmol) obtained after the isomerization (70 % *exo*,*exo*-, 19 % *endo*,*exo*-, and ~1 % *endo*,*endo*-isomer) in pentane (400 mL). This solution was cooled in an ice-salt bath under a sweep of nitrogen, and a solution of bromine (5.12 g, 32 mmol) in pentane (80 mL) was added dropwise at such a rate as to keep the temperature under 0°C. A precipitate of dibromides formed, colorless at the beginning, yellow-orange towards the end of the addition. The solvent was evaporated under reduced pressure (white clouds of HBr!), the residue, a mixture of isomeric dibromides (GC, 160 to 250°C, 15°C$\,min^{-1}$, a set of peaks, t_r = 7–7.9 min; the weight of solids corresponded to a quantitative yield of dibromides **7**), was dissolved in anhydrous MeOH (350 mL). A solution of sodium (5.9 g, 0.256 mol, 5-fold excess) in anhydrous MeOH (175 mL) was added under nitrogen, and the resulting mixture was heated under reflux for 2 h, cooled to ambient temperature and poured into a solution of NH_4Cl (15 g) in water (1.5 L). The turbid mixture was extracted with Et_2O (500 + 450 +

2×300 mL), the combined extracts, which contained (GC, 160 to 250 °C, 15 °C min^{-1}) 37 % of the title compound **8** (t_r = 4.25–4.4 min), and a number of monobromides (t_r = 5.3–6.0 min), were dried overnight ($MgSO_4$). The organic solution was concentrated to 50–70 mL on a rotary evaporator, and the residual solution left at −60 °C for 4–6 h. Fast filtration afforded slightly grayish diester **8** (925 mg, 13.2 %; >99 %, GC). Recrystallization from hexane or methanol gave very light, colorless crystals of pure diester **8** (>99 %, GC). In several experiments the average yield for this step was 13–14 %. An X-ray crystal structure analysis has been reported in the preliminary communication.[7] ^{1}H NMR (250 MHz, C_6D_6, $\delta(C_6D_5H) = 7.16$ ppm): $\delta = 2.26$ (m, 4H), 2.86 (m, 4H), 3.31 (s, 6H), 3.58 (m, 2H); ^{13}C NMR (62.9 MHz, $CDCl_3$): $\delta = 45.8$ [C-3(4,9,11)], 47.9 [C-5-(7,8,12)], 51.5 [C-2(10)], 61.1 [CH_3 or C-1(6)], 61.2 [C-1(6) or CH_3], 171.9 (C=O).

Octahedrane-2,10-dicarboxylic acid (9): A mixture of diester **8** (1.09 g, 4 mmol) and a solution of NaOH (1.6 g, 40 mmol) in methanol/water 1:1 (80 mL) was heated under reflux for 1.5 h with stirring under nitrogen. The colorless solid dissolved completely. After cooling in an ice-bath, conc. HCl (5 mL) was added. The voluminous colorless precipitate was filtered off, washed with acetone (2×5 mL), and carefully dried under reduced pressure ($<1\times10^{-2}$ Torr) up to a constant weight to give **9** as a colorless powder (970 mg, 99 %).

[D_{3d}]-Octahedrane (heptacyclo[6.4.0.0^{2,4}.0^{3,7}.0^{5,12}.0^{6,10}.0^{9,11}]dodecane, 1): In a 250 mL Schlenk flask, equipped with a magnetic stirring bar and a reflux condenser with a bubbler, were placed diacid **9** (606 mg, 2.48 mmol) and freshly distilled $SOCl_2$ (25 mL), and the mixture was heated with stirring under reflux for 4 h under a slow stream of nitrogen. The reaction mixture was then cooled to ambient temperature, and the excess of thionyl chloride was removed in vacuo. The yield of diacid dichloride **10** was virtually quantitative. To the residue was added anhydrous benzene (100 mL), sodium pyridine-2-thione-*N*-oxide (Barton salt; 900 mg, 6.03 mmol), 4-dimethylaminopyridine (61 mg, 0.5 mmol), and this mixture was stirred at RT under nitrogen for 30 min (strong direct light should be avoided). *tert*-Butylmercaptane (1.17 g, 13 mmol, **a well ventilated hood is essential!**) was added, and the greenish-yellow reaction mixture under nitrogen was heated under reflux for 2.5 h. AIBN (65 mg, 0.4 mmol) was added, and the resulting suspension was irradiated with a 500 W tungsten lamp under nitrogen at ambient temperature with stirring in a water bath until the yellow color had completely disappeared (5×0.5 h). The reaction mixture was subjected to flash chromatography on silica gel (15 g; 100 mL pentane). The benzene fraction, clearly visible in the column, and the first 25–35 mL of pentane contained the main part of the product **1** (GC, 40 to 140 °C, 15 °C min^{-1}, t_r = 5.9–6.0 min; 100 to 250 °C, 15 °C min^{-1}, t_r ~2.7 min). The solvents were carefully removed by distillation at ambient pressure, the creamy white, slightly waxy residue was sublimed with gentle heating in vacuo (5–7 mm Hg) giving heavy colorless crystals of **1** (214 mg, 55 %; >95 % purity by GC). Repeated sublimation gave a sample of high purity (>99 %), m.p. 110 °C (DSC). The yield of **1** in several runs varied from 50–70 %, and the purity from 95 to >99 %. ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 1.60$ [6H, 2(3,4,9,10,11)-H], 3.00 [6H, 1(5,6,7,8,12)-H]; ^{13}C NMR (125.7 MHz, $CDCl_3$): $\delta = 33.6$ [$^1J_{C,H}$ = 170 Hz, C-2(3,4,9,10,11)], 62.3 [$^1J_{C,H}$ = 140 Hz, C-1(5,6,7,8,12)]. An X-ray crystal structure analysis has been reported in the preliminary communication.[7] MS (EI): *m/z* (%): 157 (11), 156 (51) [M^+], 155 (45), 154 (20), 153 (32), 152 (20), 151 (6), 142 (8), 141 (48), 139 (6), 129 (29), 128 (46), 127 (25), 126 (6), 116 (9), 115 (51), 103 (5), 102 (12), 92 (25), 91 (100), 89 (14), 79 (10), 78 (57), 77 (41), 76 (29), 75 (11), 74 (8), 65 (34), 64 (21), 63 (31), 62 (10), 53 (5), 52 (26), 51 (39), 50 (28).

General procedure (GP) for the hydrogenation of [D_{3d}]-octahedrane (1): Under stirring, a suspension of platinum dioxide in acetic acid (6 mL) was prehydrogenated with H_2 under ambient pressure for 15 min. After this, a solution of octahedrane (**1**) (70 mg, 0.448 mmol) in pentane (2 mL) was added in one portion, and the mixture was stirred at ambient temperature for the time indicated, monitoring the volume of consumed hydrogen. The reaction mixture was then diluted with pentane (50 mL), washed with H_2O (2×50 mL), sat. $NaHCO_3$ solution (50 mL), brine (50 mL), dried and concentrated under reduced pressure.

Hydrogenation of [D_{3d}]-octahedrane (1) with one equivalent of hydrogen: Octahedrane **1** (70 mg, 0.448 mmol) and PtO_2 (20 mg, 0.088 mmol, 20 mol %) were hydrogenated according to the GP. After 15 min, 10.0 mL (1 equiv) of hydrogen had been consumed, and work-up gave a mixture (72 mg, 100 %) which contained 28 % starting material **1**, 21 % hexacyclo[6.4.0.0^{2,6}.0^{3,11}.0^{4,9}.0^{5,7}]dodecane (**13**), 43 % pentacyclo[6.4.0.0^{2,6}.0^{3,11}.0^{4,9}]dodecane (**16**), and 8 % pentacyclo[6.3.1.0^{2,7}.0^{3,10}.0^{5,9}]-dodecane (**17**) according to the NMR spectra of the mixture.

Compound 13: ^{13}C NMR (62.9 MHz, $CDCl_3$): $\delta = 34.7$ (2 CH), 37.1 (CH), 39.7 (2 CH_2), 40.8 (CH), 44.3 (CH), 56.1(2 CH), 58.0 (2 CH), 59.8 (CH).

Compound 16: ^{1}H NMR (250 MHz, $CDCl_3$): $\delta = 1.81$–1.86 (m, 8H), 1.95–2.05 (m, 2H), 2.01–2.17 (m, 2H), 2.30–2.35 (m, 2H), 2.41–2.49 (m, 2H); ^{13}C NMR (62.9 MHz, $CDCl_3$): $\delta = 36.8$ (2 CH), 41.0 (2 CH_2), 42.6 (2 CH), 42.8 (2 CH_2), 51.3 (2 CH), 53.2 (2 CH).

Compound 17: ^{13}C NMR (62.9 MHz, $CDCl_3$): $\delta = 22.4$ (2 CH), 41.6 (4 CH_2), 42.1 (2 CH), 52.3 (4 CH).

Hydrogenation of [D_{3d}]-octahedrane (1) with two equivalents of hydrogen: Octahedrane **1** (70 mg, 0.448 mmol) and PtO_2 (30 mg, 0.132 mmol, 30 mol %) were hydrogenated according to the GP. After 15 min, 20.1 mL (2 equiv) of hydrogen had been consumed, and work-up gave a mixture (72 mg, 100 %) which contained **16** (87 %), and **17** (13 %).

Photochlorination of [D_{3d}]-octahedrane (1) with *tert*-butyl hypochlorite: A solution of **1** (187 mg, 1.2 mmol) and *tert*-butyl hypochlorite (195 mg, 1.8 mmol) in CCl_3F (25 mL) was irradiated under nitrogen at −40 to −45 °C (dry ice-methanol bath) in a 50 mL Pyrex photo reactor with a 150 W medium-pressure Hg lamp for 1.5 h. GC and GC-MS monitoring (130 °C, 3 min, then 15 °C min^{-1} up to 250 °C, ratio of peak areas without calibration coefficients) showed only traces of 1- and 2-monochlorooctahedranes (t_r = 3.35 and 3.29 min, respectively), but about 5–7 % higher molecular mass product (t_r ~6 min), which had the molecular formula $C_{12}H_{12}Cl_2$ (GC-MS) and was shown to be 4,6-dichlorohexacyclo[9.1.0.0^{2,7}.0^{3,10}.0^{5,9}.0^{8,12}]dodecane (**30**), along with ~90 % starting material **1** (t_r = 2.1–2.2 min). An additional amount of *tert*-butyl hypochlorite (195 mg, 1.8 mmol) in CCl_3F (5 mL) was added, and the irradiation was continued for 1 h, after which the mixture contained 12 % monochlorides, <1 % dichlorides (t_r = 4.5–4.7 min) and ~3.5 % trichloride (t_r ~6.8 min). Another batch of *tert*-butyl hypochlorite (195 mg, 1.8 mmol) in CCl_3F (5 mL) was added, and the mixture was irradiated for 2 h. According to GC, the resulting mixture contained about 45 % starting hydrocarbon **1**, ~35 % 1- and 2-chlorooctahedranes in a ratio of ~4:1, 4–5 % dichlorides, ~5 % trichlorides (t_r = 6.65 and 6.8 min), and traces of tetrachloro derivatives (t_r =7.4–7.8 min). The turbid reaction mixture was concentrated, the residue (320 mg) was separated by flash chromatography on silica gel (30 g; pentane). First, octahedrane **1** (47 mg, 25 %), then 2-chlorooctahedrane **29** (~5 mg, 2 %; >90 % pure GC), 1-chlorooctahedrane (**28**) (23 mg, 10 %; >94 % pure GC), as well as di- and trichlorides were eluted.

1-Chlorooctahedrane (28): Low-melting colorless solid; ^{1}H NMR: δ = 1.63–1.77 (m, 3H), 1.77–1.86 (m, 2H) [3(4),9(11),10-H]; 1.90–1.97 (deformed t, *J* = 7 Hz, 1H, 2-H), 3.02–3.18 (m, 3H, 5(7),6-H), 3.20–3.28 (m, 2H, 8(12)-H); ^{13}C NMR: δ = 32.8, 33.3 [C-3(4), C-9(11)]; 34.1 (C-10), 38.6 (C-2), 60.9 (C-6), 62.0 [C-5(7)], 70.5 [C-8(12)], 92.6 (C-1); MS (EI): *m/z* (%): 193 (2) [M^+], 192 (9) [M^+], 191 (4) [M^+], 190 (26) [M^+], 156 (13), 155 (100), 154 (34), 153 (47), 152 (24), 151 (13), 149 (6), 129 (16), 128 (26), 127 (47), 126 (16), 125 (99), 115 (19), 114 (10), 112 (23), 102 (8), 101 (5), 92 (7), 91 (79), 90 (7), 89 (10), 78 (29), 77 (32), 76 (23), 75 (14), 74 (7), 73 (5), 65 (9), 64 (10), 63 (18), 62 (7), 52 (7), 51 (25), 50 (15); HRMS: *m/z*: calcd for $C_{12}H_{11}Cl$: 190.0549; found: 190.0549.

2-Chlorooctahedrane (29): Light-yellow oil; ^{1}H NMR: δ = 1.65 (m, 3H), 2.0 (m, 2H), 2.96–3.06 (m, 1H), 3.1–3.3 (br, m, 5H); ^{13}C NMR: δ = 32.9 (C-10), 33.4 [C-9(11)], 42.8 [C-3(4)], 59.1 [C-5(7) or C-8(12)], 61.5 (C-6), 62.4 (C-2), 63.5 [C-8(12) or C-5(7)], 70.2 (C-1); MS (EI): *m/z* (%): 193 (0.5) [M^+], 192 (3) [M^+], 191 (2) [M^+], 190 (10) [M^+], 156 (4), 155 (41), 154 (15), 153 (27), 152 (15), 151 (6), 129 (8), 128 (15), 127 (41), 126 (13), 125 (100), 115 (11), 114 (8), 112 (14), 102 (5), 91 (59), 89 (7), 78 (18), 77 (19), 76 (16), 75 (8), 65 (6), 64 (6), 63 (14), 62 (5), 52 (5), 51 (16), 50 (10); HRMS: *m/z*: calcd for $C_{12}H_{11}Cl$: 190.0549; found: 190.0549.

In another run, a solution of octahedrane **1** (430 mg, 2.75 mmol) and *tert*-butyl hypochlorite (450 mg, 4.14 mmol) in CCl_3F (100 mL; dist. from P_2O_5) was irradiated at −40 to −45 °C with a 450 W medium-pressure Hg lamp for 30 min. The gas chromatogram showed about 3 % 1- and 2-chlorooctahedranes, ~17 % dichloride **30** and ~80 % starting hydrocarbon **1**. A solution of *tert*-butyl hypochlorite (675 mg, 6.22 mmol) in CCl_3F (5 mL) was added and irradiation was continued for 30 min. Separation of the resulting mixture on silica gel (56 g) gave starting material **1** (75 mg, 17 %), a mixture of **1** and 2-chlorooctahedrane (**29**) ~4:6 (50 mg; i.e., ~5 % **1** and 6 % 2-chlorooctahedrane **29**), 1-chlorooctahedrane **28** (47 mg, 9 %), a mixture of di- and trichlorides and after that dichloride **30** (76 mg, 12 %).

10,12-Dichlorohexacyclo[6.4.0.0^{2,6}.0^{3,11}.0^{4,9}.0^{5,7}]dodecane (30): Clear oil; ^{1}H NMR: δ = 2.06 [ddd, J=6.8, 3.0, 1.5 Hz, 2 H, 5(6)-H], 2.23 (td, J= 6.8, 4.3 Hz, 1 H, 7-H), 2.45 (m, 1 H, 8-H), 2.68 [tm, J=~4.5 Hz, 2 H, 1(9)-H], 2.75 (dt, J=5.5, 1.5 Hz, 1 H, 11-H), 3.18 (tdt, J=7, 5.5, 1.5 Hz, 1 H, 3-H), 3.30 [m, 2 H, 2(4)-H], 4.14 [brs, 2 H, 10(12)-H]; ^{13}C NMR: δ=34.9 [C-5(6)], 40.5 (C-7), 46.3 (C-8), 53.6 [C-2(4)], 56.7 (C-3), 57.4 (C-11), 64.1 [C-1(9)], 66.9 (C-Cl). The signal assignments in the NMR spectra were confirmed by CH correlation and COSY experiments. MS (EI): m/z (%): 230 (2) [M^+], 229 (1) [M^+], 228 (11) [M^+], 227 (3) [M^+], 226 (17) [M^+], 193 (6), 192 (6), 191 (18), 190 (13), 162 (5), 160 (6), 156 (13), 155 (92), 154 (19), 153 (24), 152 (17), 151 (15), 141 (11), 129 (15), 128 (39), 127 (47), 126 (41), 125 (100), 117 (16), 116 (13), 115 (47), 114 (20), 113 (32), 112 (11), 103 (13), 102 (14), 101 (22), 100 (12), 99 (7), 92 (7), 91 (97), 89 (18), 80 (6), 79 (64), 78 (42), 77 (85), 76 (32), 75 (16), 74 (8), 73 (7), 67 (13), 66 (16), 65 (23), 64 (14), 63 (25), 62 (9), 52 (14), 51 (41), 50 (18), 49 (7).

Bromination of [D_{3d}]-octahedrane (1): A mixture of **1** (100 mg, 0.64 mmol), CBr_4 (0.5 g, 1.5 mmol), fluorobenzene (6 mL), 50 % aqueous NaOH (2.7 mL), and tetrabutylammonium bromide (16 mg, 0.05 mmol) was stirred at 70 °C for 120 h, then diluted with water (10 mL), and the mixture extracted with CH_2Cl_2 (3×5 mL). The organic extracts were washed with water (3×3 mL) and dried over Na_2SO_4; the solvents were removed in vacuo. Column chromatography on silica gel (50 g; pentane) gave the starting hydrocarbon **1** (31 mg), 1-bromooctahedrane (**31**; 64 mg, 43 %) and 10,12-dibromohexacyclo[6.4.0.0^{2,6}.0^{3,11}.0^{4,9}.0^{5,7}]dodecane (**32**; 24 mg, 12 %).

1-Bromooctahedrane (31): Colorless solid; m.p. 83–84 °C (*n*-hexane); ^{1}H NMR: δ=1.65–1.78 (m, 3 H), 1.71–1.87 (m, 2 H), 2.04 (t, J=7 Hz, 1 H), 3.11 (m, 3 H), 3.38 (m, 2 H); ^{13}C NMR: δ=33.1, 33.3 [C-3(4), C-9(11)], 33.8 (C-10), 39.8 (C-2), 60.7 (C-6), 62.4 [C-5(7)], 71.6 [C-8(12)], 84.5 (C-1); MS (EI): m/z (%): 236/234 (11, 11) [M^+], 171 (72), 169 (74), 190 (26), 156 (13), 155 (100), 154 (34), 153 (47), 152 (24), 151 (13), 149 (6), 155 (100), 129 (16), 139 (3), 129 (21), 128 (22), 127 (15), 126 (4), 115 (18), 78 (23), 77 (25), 76 (27), 64 (7), 63 (10), 51 (15), 50 (6); elemental analysis calcd for $C_{12}H_{11}Br$ (235.1): C 61.30, H 4.72, Br 33.98; found: C 61.49, H 4.57, Br 34.16.

10,12-Dibromohexacyclo[6.4.0.0^{2,6}.0^{3,11}.0^{4,9}.0^{5,7}]dodecane (32): Colorless solid; m.p. 93–94 °C (*n*-hexane); ^{1}H NMR: δ=2.07 (m, 2 H), 2.31 (m, 1 H), 2.50 (m, 1 H), 2.81 (m, 2 H), 3.13 (m, 1 H), 3.22 (m, 1 H), 3.42 (m, 2 H), 4.28 (brs, 2 H); ^{13}C NMR: δ=34.7 [C-5(6)], 41.3 (C-7), 47.2 (C-8), 54.8 [C-2(4)], 56.8 (C-3), 58.3 (C-11), 58.6 [C-10(12)], 64.4 [C-1(9)]; MS (EI): m/z (%): 318/316/314 (2/5/2) [M^+], 229 (1), 228 (11), 227 (3), 226 (17), 193 (6), 192 (6), 191 (18), 190 (13), 162 (5), 160 (6), 156 (13), 155 (92), 154 (19), 153 (24), 152 (17), 151 (15), 141 (11), 129 (15), 128 (39), 127 (47), 126 (41), 125 (100), 117 (16), 116 (13), 115 (47), 114 (20), 113 (32), 112 (11), 103 (13), 102 (14), 101 (22), 100 (12), 99 (7), 92 (7), 91 (97), 89 (18), 80 (6), 79 (64), 78 (42), 77 (85), 76 (32), 75 (16), 74 (8), 73 (7), 67 (13), 66 (16), 65 (23), 64 (14), 63 (25), 62 (9), 52 (14), 51 (41), 50 (18), 49 (7); elemental analysis calcd for $C_{12}H_{12}Br_2$ (316.0): C 45.61, H 3.83, Br 50.57; found: C 45.39, H 3.87, Br 50.37.

Bromination of 2,4-dehydroadamantane (33): A mixture of hydrocarbon **33** (130 mg, 0.97 mmol), CBr_4 (0.6 g, 1.81 mmol), CH_2Cl_2, (3 mL), 50 % aqueous NaOH (2 mL), and tetrabutylammonium bromide (16 mg, 0.05 mmol) was stirred at room temperature for 120 h, then diluted with water (10 mL) and extracted with CH_2Cl_2 (3×5 mL). The extracts were washed with water, dried over Na_2SO_4, and the solvents removed in vacuo. Column chromatography on silica gel (60 g; pentane) gave starting hydrocarbon **33** (42 mg) and 7-bromo-2,4-dehydroadamantane (**35**; 113 mg, 54 %). ^{1}H NMR (250 MHz, $CDCl_3$): δ =1.43–1.6 (m, 4 H), 2.03 (m, 4 H), 2.18 (m, 1 H), 2.21 (m, 4 H); ^{13}C NMR: δ = 22.4, 26.7, 36.5, 40.2, 44.9, 51.3, 65.9; MS (EI): m/z (%): 214/212 (7/7) [M^+], 170 (6), 133 (81), 117 (11), 105 (22), 91 (84), 79 (100), 78 (65), 77 (24), 65 (13), 55 (8); elemental analysis calcd for $C_{10}H_{13}Br$ (213.1): C 56.36, H 6.15, Br 37.49; found: C 56.39, H 6.28, Br 37.77.

Computational methods: Geometries were optimized at the B3LYP/6-311+G* and MP2/6-31G* (hydrocarbons), as well as at B3LYP/6-31G* (reactions of **1** with radicals) levels of theory including frequency analyses to disclose the nature of the stationary points (Number of imaginary frequencies, $N_{\mathrm{im}}=0$ for minima and 1 for transition structures) as implemented in the Gaussian 03 program package.[44] The G_{298}-values were computed at the B3LYP/6-31G* level. The reaction pathways along both directions from the transition structures were followed by the IRC method.[45]

Acknowledgements

This work was supported by the State of Niedersachsen, the Volkswagenstiftung, the Deutsche Forschungsgemeinschaft, the Ukrainian Science Foundation, the Fonds der Chemischen Industrie, and NATO Science Programs, as well as Bayer and Hoechst AG (chemicals). The authors are indebted to Prof. Henning Menzel, Technische Universität Braunschweig, for DSC measurements on [D_{3h}]-octahedrane and to Dr. Burkhard Knieriem, Göttingen, for his careful proofreading of the final manuscript.

---

[1] J. E. Dahl, S. G. Liu, R. M. K. Carlson, *Science* **2003**, *299*, 96–99.

[2] A. P. Marchand, *Science* **2003**, *299*, 52–53.

[3] a) R. C. Fort, *Adamantane: The Chemistry of Diamondoid Molecules*, Marcel Dekker, New York, **1976**; b) G. J. Lees, *DRUGS* **2000**, *59*, 33–78.

[4] a) P. v. R. Schleyer, in *Cage Hydrocarbons* (Ed.: G. A. Olah), Wiley, New York, **1990**, pp. 1–38; b) A. Baxter, J. Bent, K. Bowers, M. Braddock, S. Brough, M. Fagura, M. Lawson, T. McInally, M. Mortimore, M. Robertson, R. Weaver, P. Webborn, *Bioorg. Med. Chem. Lett.* **2003**, *13*, 4047–4050.

[5] G. W. Schriver, D. J. Gerson, *J. Am. Chem. Soc.* **1990**, *112*, 4723–4728.

[6] It may appear unexpected that [D_{3d}]-octahedrane **1** is the most stable hydrocarbon in the $(CH)_{12}$ family. However, in view of the fact that a [12]annulene is antiaromatic and strongly distorted, this finding is not surprising. Among other $(CH)_{12}$ hydrocarbons we found the homoaromatic 7-cyclopenta-2,4-dienylcyclohepta-1,3,5-triene is the closest in energy to **1** ($\Delta\Delta E$=1.8 kcal mol^{-1} at B3LYP/6-311+G** in favor of **1**).

[7] For a preliminary report on the preparation and structure of **1** see: C.-H. Lee, S. Liang, T. Haumann, R. Boese, A. de Meijere, *Angew. Chem.* **1993**, *105*, 611–613; *Angew. Chem. Int. Ed. Engl.* **1993**, *32*, 559–561.

[8] R. T. Taylor, M. W. Pelter, L. A. Paquette, *Org. Synth.* **1990**, *68*, 198–205.

[9] G. Wilkinson, *Org. Synth.* **1963**, *4*, 473–478.

[10] L. A. Paquette, M. J. Wyvratt, H. C. Berk, R. E. Moerck, *J. Am. Chem. Soc.* **1978**, *100*, 5845–5855.

[11] a) D. H. R. Barton, D. Crich, W. B. Motherwell, *Tetrahedron* **1985**, *41*, 3901–3924; b) D. H. R. Barton, Y. Hervé, P. Potier, J. Thierry, *Tetrahedron* **1988**, *44*, 5479–5486.

[12] A. B. McEwen, P. v. R. Schleyer, *J. Org. Chem.* **1986**, *51*, 4357–4368.

[13] D. Moran, H. L. Woodcock, Z. Chen, H. F. Schaefer III, P. v. R. Schleyer, *J. Am. Chem. Soc.* **2003**, *125*, 11442–11451.

[14] Z. X. Wang, P. v. R. Schleyer, *J. Am. Chem. Soc.* **2003**, *125*, 10484–10485.

[15] J. C. Gallucci, C. W. Doecke, L. A. Paquette, *J. Am. Chem. Soc.* **1986**, *108*, 1343–1344.

[16] J. M. Schulman, T. Venanzi, R. L. Disch, *J. Am. Chem. Soc.* **1975**, *97*, 5335–5339.

[17] a) T. Clark, T. McO' Knox, H. Mackle, M. A. McKervey, *J. Chem. Soc. Chem. Commun.* **1975**, 666–667; b) H. D. Beckhaus, C. Rüchardt, D. R. Lagerwall, L. A. Paquette, F. Wahl, H. Prinzbach, *J. Am. Chem. Soc.* **1994**, *116*, 11775–11778, and references therein.

[18] C.-Y. Zhao, Y. Zhang, X.-Z. You, *J. Phys. Chem. A* **1997**, *101*, 5174–5182.

[19] C. W. Earley, *J. Phys. Chem. A* **2000**, *104*, 6622–6627.

[20] E. P. Hunter, S. G. Lias, *J. Phys. Chem. Ref. Data* **1998**, *27*, 413.

[21] a) E. M. Engler, J. D. Andose, P. v. R. Schleyer, *J. Am. Chem. Soc.* **1973**, *95*, 8005–8025; b) H. D. Beckhaus, C. Rüchardt, D. R. Lagerwall, L. A. Paquette, F. Wahl, H. Prinzbach, *J. Am. Chem. Soc.* **1995**, *117*, 8885; c) J. M. Schulman, R. L. Disch, *J. Am. Chem. Soc.* **1984**, *106*, 1202–1204.

[22] R. L. Disch, J. M. Schulman, *J. Phys. Chem.* **1996**, *100*, 3504–3506.

[23] Platinum dioxide is known to be the most efficient catalyst for hydrogenolytic ring openings of unactivated cyclopropanes in hydrocarbons: compare S. I. Kozhushkov, R. R. Kostikov, A. P. Molchanov, R. Boese, J. Benet-Buchholz, P. R. Schreiner, C. Rinderspacher, I. Ghiviriga, A. de Meijere, *Angew. Chem.* **2001**, *113*, 179–182; *Angew. Chem. Int. Ed.* **2001**, *40*, 180–183, and references therein.

[24] Oligocyclic $(CH)_n$ cage hydrocarbons with more than one cyclopropane moiety adjacent to each other, like the $(CH)_{10}$ hydrocarbon diademane (hexacyclo$[4.4.0.0^{2,10}.0^{3,5}.0^{4,8}.0^{7,9}]$decane), may undergo rearrangement in contact with platinum(0) prior to hydrogenolytic ring opening, compare ref. [25].

[25] a) E. Osawa, H. Musso, *Angew. Chem.* **1983**, *95*, 1–12; *Angew. Chem. Int. Ed. Engl.* **1983**, *22*, 1–12, and references therein.

[26] a) D. Kaufmann, O. Schallner, L.-U. Meyer, H.-H. Fick, A. de Meijere, *Chem. Ber.* **1983**, *116*, 1377–1385; b) D. Bosse, A. de Meijere, *Tetrahedron Lett.* **1975**, 871–874.

[27] H. Stetter, C. Wulff, *Chem. Ber.* **1960**, *93*, 1366–1371.

[28] I. K. Moiseev, Y. N. Klimochkin, M. N. Zemtsova, P. L. Trakhtenberg, *Zhurn. Org. Khim.* **1984**, *20*, 1435–1438.

[29] A. A. Fokin, P. R. Schreiner, *Chem. Rev.* **2002**, *102*, 1551–1593.

[30] A. A. Fokin, P. R. Schreiner, *Adv. Synth. Catal.* **2003**, *345*, 1035–1052.

[31] a) T. M. Gund, P. v. R. Schleyer, G. D. Unruh, G. J. Gleicher, *J. Org. Chem.* **1974**, *39*, 2995–3003; b) A. A. Fokin, B. A. Tkachenko, P. A. Gunchenko, D. V. Gusev, P. R. Schreiner, *Chem. Eur. J.* **2005**, *11*, in press (DOI: 10.1002/chem.200500031).

[32] L. A. Paquette, *Chem. Rev.* **1989**, *89*, 1051–1065.

[33] L. A. Paquette, J. C. Weber, T. Kobayashi, Y. Miyahara, *J. Am. Chem. Soc.* **1988**, *110*, 8591–8599.

[34] The 1- and 2-octahedryl cations have virtually the same energy at B3LYP/6-31G*.

[35] Recent studies on the mechanisms of alkane functionalizations with oxidizing electrophiles (A. A. Fokin, T. E. Shubina, P. A. Gunchenko, S. D. Isaev, A. G. Yurchenko, P. R. Schreiner, *J. Am. Chem. Soc.* **2002**, *124*, 10718–10727) revealed that the transition structures are characterized by significant charge transfer to the electrophile, and the hydrocarbon moieties resemble the respective radical cation structures (H-coupled electron transfer). Compound **1** forms a radical cation with one elongated C−C bond (1.855 Å, B3LYP/6-31G*) in the cyclopropane moiety showing that the most favorable reaction path with electrophilic reagents involves C−C bond breaking.

[36] A. A. Fokin, O. Lauenstein, P. A. Gunchenko, P. R. Schreiner, *J. Am. Chem. Soc.* **2001**, *123*, 1842–1847.

[37] A. de Meijere, O. Schallner, C. Weitemeyer, W. Spielmann, *Chem. Ber.* **1979**, *112*, 908–935.

[38] P. R. Schreiner, O. Lauenstein, E. D. Butova, P. A. Gunchenko, I. V. Kolomitsin, A. Wittkopp, G. Feder, A. A. Fokin, *Chem. Eur. J.* **2001**, *7*, 4996–5003.

[39] O. Lauenstein, A. A. Fokin, P. R. Schreiner, *Org. Lett.* **2000**, *2*, 2201–2204.

[40] G. W. Griffin, A. P. Marchand, *Chem. Rev.* **1989**, *89*, 997–1010.

[41] a) A. C. Udding, J. Strating, H. Wynberg, *J. Chem. Soc. Chem. Commun.* **1966**, 657–658; b) S. D. Isaev, A. G. Yurchenko, F. N. Stepanov, G. G. Kolyada, S. S. Novikov, *Zhurn. Org. Khim.* **1973**, *9*, 430.

[42] a) A. A. Fokin, S. A. Peleshanko, P. A. Gunchenko, D. V. Gusev, P. R. Schreiner, *Eur. J. Org. Chem.* **2000**, 3357–3362; b) L. D'Accolti, A. Dinoi, C. Fusco, A. Russo, R. Curci, *J. Org. Chem.* **2003**, *68*, 7806–7810.

[43] a) A. C. Udding, J. Strating, H. Wynberg, *Tetrahedron Lett.* **1968**, 1345–1350; b) K. J. Shea, P. S. Skell, *J. Am. Chem. Soc.* **1973**, *95*, 6728–6734.

[44] Gaussian 03, revision B.03, M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, J. A. Montgomery, Jr., T. Vreven, K. N. Kudin, J. C. Burant, J. M. Millam, S. S. Iyengar, J. Tomasi, V. Barone, B. Mennucci, M. Cossi, G. Scalmani, N. Rega, G. A. Petersson, H. Nakatsuji, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, M. Klene, X. Li, J. E. Knox, H. P. Hratchian, J. B. Cross, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, P. Y. Ayala, K. Morokuma, G. A. Voth, P. Salvador, J. J. Dannenberg, V. G. Zakrzewski, S. Dapprich, A. D. Daniels, M. C. Strain, O. Farkas, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. V. Ortiz, Q. Cui, A. G. Baboul, S. Clifford, J. Cioslowski, B. B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, M. Challacombe, P. M. W. Gill, B. Johnson, W. Chen, M. W. Wong, C. Gonzalez, and J. A. Pople, Gaussian, Inc., Pittsburgh PA, 2003.

[45] C. Gonzalez, H. B. Schlegel, *J. Phys. Chem.* **1990**, *94*, 5523–5527.

Received: April 27, 2005