Hydrogenation of [5]- and [6]Metacyclophane: Reactivity and Thermochemistry

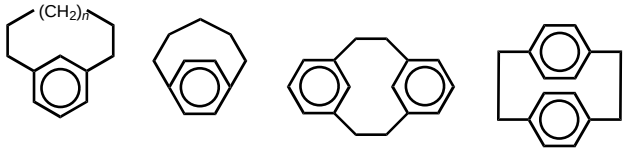
Maurice J. van Eis,[a] Geerlig W. Wijsman,[a] Willem H. de Wolf,[a] Friedrich Bickelhaupt,*[a] Donald W. Rogers,*[b] Huub Kooijman,[c] and Anthony L. Spek[c][+]

Abstract: The course of the hydrogenation of [5]- and [6]metacyclophane (**1b** and **1c**) and their thermochemistry is described. Both compounds are hydrogenated rapidly (within 10 s) to furnish the bridgehead olefins **13b** and **12c**. The accompanying hydrogenation enthalpies are -220 and -141 kJ mol^{-1}, respectively. Strain energies (SE) and olefinic strains (OS) of a number of bridgehead olefins have been evaluated by DFT calculations; it was concluded that **13b** belongs to the class of hyperstable olefins which correlates nicely with its reluctance to undergo hydrogenation. By combining experimental hydrogenation enthalpies and DFT calculations, SE of 187 and 121 kJ mol^{-1} were derived for **1b** and **1c**.

Keywords: calorimetry · cyclophanes · DFT calculations · hyperstable olefins · strain energy

Introduction

Since the pioneering work of Cram in the 1950s, small cyclophanes have continued to fascinate chemists by displaying an exceptionally rich and versatile chemistry.[1] It has been recognised[2] that these compounds are fully aromatic as judged from several physical criteria such as X-ray crystal structures[2a,b] and NMR data,[2c] in spite of a considerable degree of bending of their benzene rings. Their high reactivity stems essentially from a high ground state energy; the driving force for most reactions, which are often unprecedented in common aromatic chemistry, is the release of strain. This is displayed most clearly by the smallest members of the series, [4]metacyclophane (**1a**, unstable at $-60\,^{\circ}$C),[3] [5]metacyclophane (**1b**),[4] and [5]paracyclophane (**2**, unstable at room temperature) (Scheme 1).[5]



1a: $n = 0$ **2** **3** **4**
1b: $n = 1$
1c: $n = 2$

Scheme 1. Different cyclophanes.

In this context, it may seem surprising that few experimental thermochemical data for this class of compounds are available. Exceptions are [2.2]metacyclophane (**3**) and [2.2]paracyclophane (**4**) for which strain energies of 52 and 134 kJ mol^{-1}, respectively, have been derived from heat of combustion measurements.[6] By differential scanning calorimetry, the energy difference between a substituted [6]paracyclophane and its Dewar benzene isomer has been determined to be 128 kJ mol^{-1}.[7]

With respect to the small metacyclophanes, only theoretical calculations are available, but these have proven not to be consistent, as may be illustrated by the following example. Using MNDO, a value of 193 kJ mol^{-1} has been derived for the strain energy (SE) of [5]metacylophane (**1b**),[8] ab initio calculations at the STO-3G level provided SE = 234 kJ mol^{-1},[9] and recently, SE = 174 kJ mol^{-1} has been obtained by DFT calculations.[10] Clearly, it would be desirable to assess the accuracy of these calculations by comparison with experimental data such as those obtained by the determination of the heat of hydrogenation of these compounds.

[a] Prof. Dr. F. Bickelhaupt, Drs. M. J. van Eis, Dr. G. W. Wijsman,[+] Dr. W. H. de Wolf
Scheikundig Laboratorium, Vrije Universiteit
De Boelelaan 1083, 1081 HV Amsterdam (The Netherlands)
Fax.: (+31) 20-4447488
E-mail: bicklhpt@chem.vu.nl

[b] Prof. Dr. D. W. Rogers
Chemistry Department, Long Island University
Brooklyn, NY 11201 (USA)

[c] Dr. H. Kooijman, Dr. A. L. Spek[+]
Bijvoet Center for Biomolecular Research
Crystal and Structural Chemistry, Utrecht University
Padualaan 8, 3584 CH Utrecht (The Netherlands)
E-mail: spea@chem.ruu.nl

[+] address correspondence pertaining to crystallographic studies

[+] Present address:
DSM Research
Postbus 18, 6160 MG, Geleen (The Netherlands)

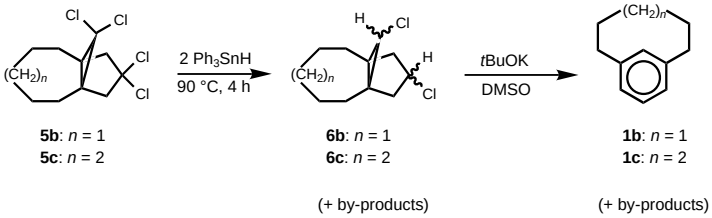
  0947-6539/00/0609-1537 $ 17.50+.50/0

Although the impact of heat of hydrogenation measurements has gradually declined since the 1970s, it should be emphasised that this method has played a vital role in establishing important concepts in chemistry such as strain and aromaticity. Hydrogenation experiments have demonstrated that *trans*-2-butene is about 4.2 kJ mol^{-1} more stable than *cis*-2-butene.[11] This is generally the case except when the double bond is incorporated in a ring containing nine or less carbon atoms. Thus, it was found that the energy released in the hydrogenation of *trans*-cyclooctene is 47.7 kJ mol^{-1} larger than that of *cis*-cyclooctene[12] which furnished a thermodynamic confirmation of the famous double bond rule of Bredt.[13] Another classical example is the hydrogenation of benzene. In contrast to the hydrogenation of cyclohexene, which is strongly exothermic (-119.7 kJ mol^{-1}),[14] the first step for the hydrogenation of benzene was derived to be slightly endothermic ($+23.4$ kJ mol^{-1}).[15] The difference between these two values (-143 kJ mol^{-1}) was considered as a (rough) measure for the resonance energy of benzene.[15, 16] An additional advantage of measuring hydrogenation enthalpies is that this method is inexpensive and unsophisticated, yet more accurate for the evaluation of small energy differences than heat of combustion measurements which suffer from the fact that the error involved in subtracting two large numbers is substantially larger.

Because of its high sensitivity, we decided to apply isoperibol[17] hydrogenation calorimetry in conjunction with calculated ΔH^{hyd}_{298} values to the smallest members of the [n]metacyclophane series in an attempt to evaluate their strain energies.

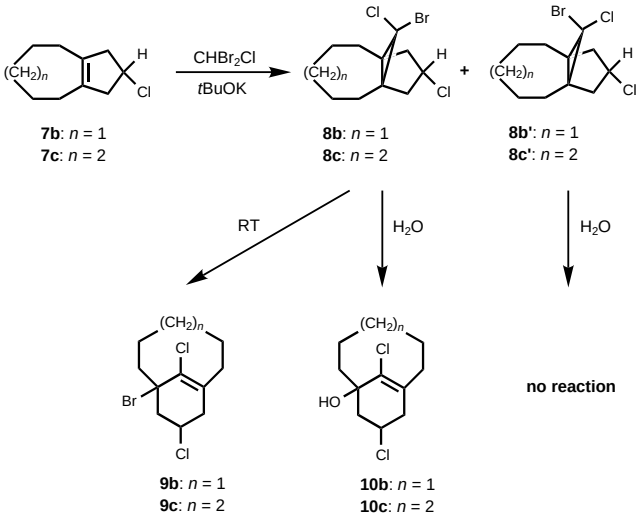
Results and Discussion

Synthesis of [5]- and [6]metacyclophane: The method most commonly used to prepare [5]- and [6]metacyclophane is briefly outlined in Scheme 2.[18]



Scheme 2. Most commonly used synthesis for **1b** and **1c**.

In the first step, a tetrachlorobicyclo[*n*.3.1]alkane (**5**) is reduced with two equivalents of triphenyltin hydride to afford a mixture of isomers of mono-, di-(**6**) and trichlorides. Without purification, this mixture is treated with a large excess of *t*BuOK in DMSO to furnish the desired unsubstituted cyclophane **1** via a two-fold HCl elimination (vide infra) as the major product; purification can be achieved by preparative GLC. One of the major disadvantages of this method is that **1b** thus obtained is usually contaminated by small amounts of its ortho-isomer (up to 10%), formed by thermal or acid-catalysed rearrangement on the GC column. Because the purity of the cyclophanes thus prepared is insufficient for an accurate evaluation of their heats of hydrogenation, we devised a slightly different, improved synthesis (Scheme 3).



Scheme 3. Synthesis of intermediates **8b′** and **8c′**.

Addition of bromochlorocarbene (from dibromochloromethane and potassium *tert*-butoxide) to the monochloride **7b** yielded a 1:1 mixture of propellanes **8b**. The isomer in which the bromine is located above the five-membered ring, **8b**, undergoes a slow disrotatory ring opening to give the anti-Bredt olefin **9b**, in analogy to rearrangements reported previously.[19] Fortunately, the remaining isomer (**8b′**) is the desired one (vide infra). Stirring a solution of **8b′** and **8b** in chloroform containing a small amount of water resulted in the conversion of **8b** to **10b**. The latter was conveniently separated from **8b′** by column chromatography on silica gel. The preparation of **8c** was achieved in an analogous fashion. Compound **8c** showed an even higher tendency to undergo solvolysis to **10c**; **8c′** was thus obtained pure. The configuration of **8c′** was established unambiguously by a single crystal X-ray structure determination (Figure 1); the analysed crystal contained **8c′** and **8c** in a ratio of 91.6:8.4.

The structure displays the expected features. As anticipated, the five-membered ring is nearly planar with its chlorine oriented in the direction opposite to the three-membered ring. The fixation of the torsion angle C2-C1-C8-C7 to approximately 0° forces the eight-membered ring into a conformation intermediate between boat and crown. Essential for the synthesis of **1b** and **1c** is the orientation of the chlorine at the three-membered ring. In **8c′**, the chlorine at C12 is exo, and based on the analogy of the ^{1}H-NMR spectra, it may be safely concluded that the chlorine at C11 is also in the *exo* position in **8b′**.

Slow addition of a solution of **8b′** in DMSO to a solution of *t*BuOK (large excess) in DMSO led to the formation of **1b** as the sole product [Scheme 4, (1a)]. After column chromatography, **1b** was obtained in 80% yield as a yellow oil with a purity grade exceeding 99% as indicated by GLC. The mechanism of this reaction deserves some comment.

0947-6539/00/0609-1538 $ 17.50+.50/0 *Chem. Eur. J.* **2000**, *6*, No. 9

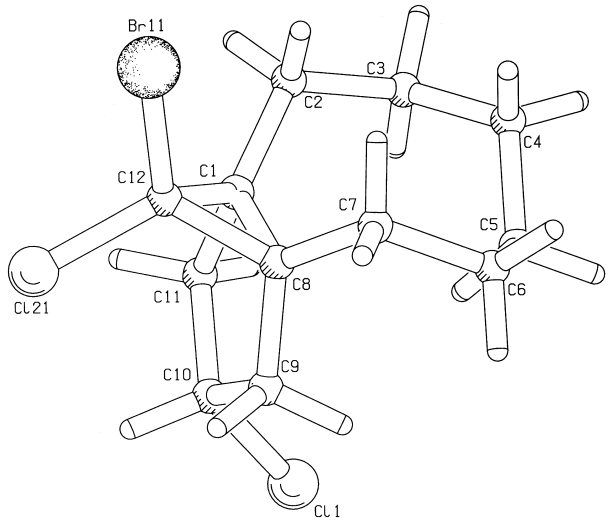
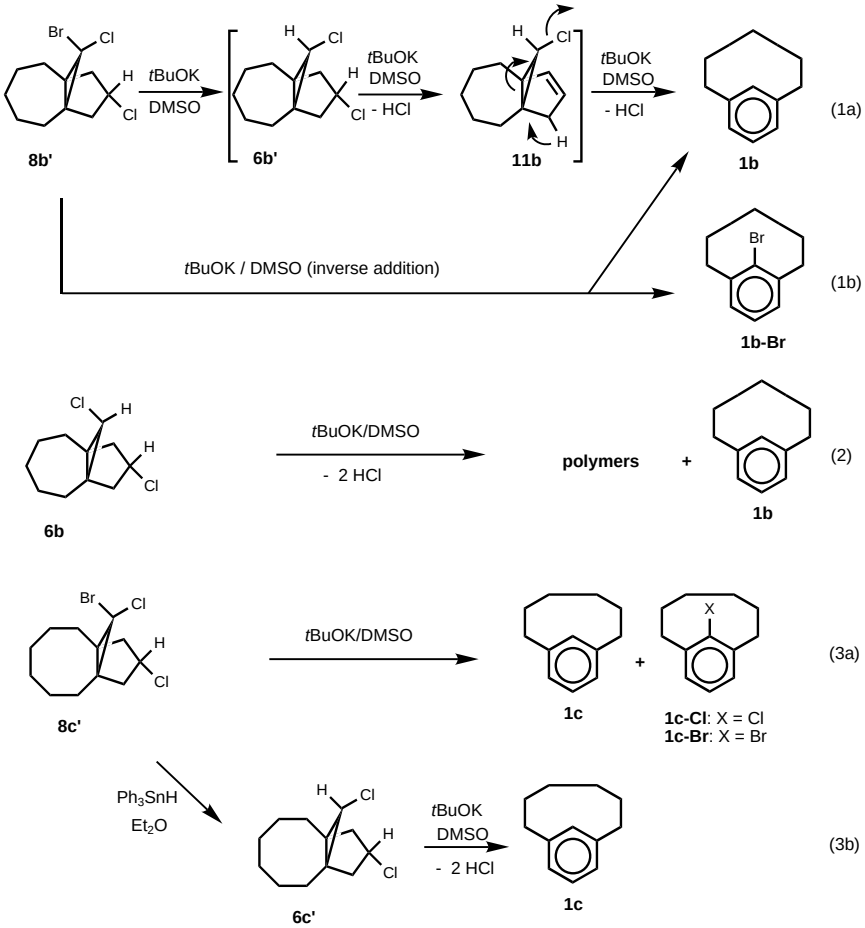


Figure 1. PLUTON plot[53] of the molecular structure of **8c′** as obtained from the crystal structure determination. The minor disorder component has been omitted for clarity.

It is assumed that the initial step in the reaction involves reduction of the bromine functionality by the dimsyl-anion, which is formed in a low steady-state concentration by deprotonation of DMSO by *tert*-butoxide. This reduction leads to **6b′** and parallels that of gem-dibromopropellanes to monobromopropellanes by treatment with *t*BuOK in DMSO.[20] Apparently, the reduction is faster than the two consecutive elimination steps which consist of a 1,2-elimination to give **11b** followed by abstraction of an allylic proton with presumably simultaneous expulsion of a chloride ion under disrotatory ring opening,[1b,c, 18, 19, 21] This is concluded from the observation that the product formation strongly depends on the mode of addition. Rapid addition of **8b′** or an inverse addition mode resulted in the formation of a 1:1 mixture of **1b** and 11-bromo[5]metacyclophane [**1b-Br**; Scheme 4, (1b)]. The reduction will be first order in dimsyl anion.[20d] On slow addition of **8b′**, the dimsyl anion is present in large excess and **8b′** is rapidly and completely reduced before it undergoes the 1,2- and 1,4-elimination. In the second case a very small amount of dimsyl anion is available which is rapidly consumed for the formation of **6b′** (which finally gives **1b**); the unreduced surplus of **8b′** is transformed by *tert*-butoxide to **1b-Br**. Noteworthy, the sterochemistry at C-11 is crucial for the course of the reaction. Elimination of **6b′** resulted in almost clean formation of **1b**; in contrast, elimination of **6b** gave polymeric material, along with traces of **1b** [Scheme 4, (2)].[21]

Different results were observed for the reaction of **8c′** with *t*BuOK [Scheme 4, (3a)]. The same procedure as described for **8b′** afforded a mixture of products containing the parent [6]metacyclophane (**1c**, 70%), but also its 12-bromo analogue (**1c-Br**, 10%) and its 12-chloro analogue (**1c-Cl**, 20%). This difference in behaviour may have several causes. Firstly, the rate of reduction to **6c′** may be diminished because of the greater flexibility of the eight-membered ring of **8c′** as compared with the seven-membered ring of **8b′**; this will hamper the approach of the dimsyl anion towards bromine. Secondly, the 1,2- and 1,4-elimination steps [proceeding via dihalo-monoene intermediates analogous to **11b** in (1a)] may be facilitated as a result of the comparatively lower strain of the resulting [6]metacyclophanes. Therefore a more convenient approach towards **1c** involved separate reduction of **8c′** with one equivalent of triphenyltin hydride to give **6c′** prior to treatment with *t*BuOK [reaction (3b)]. This adds one step to the synthetic route, but **1c** thus obtained did not need further purification.



Scheme 4. Improved synthesis of **1b** and **1c**.

Heats of hydrogenation: It has been reported previously that both **1b** and **1c** can be easily hydrogenated using palladium on charcoal as a catalyst.[1c] Because both cyclophanes

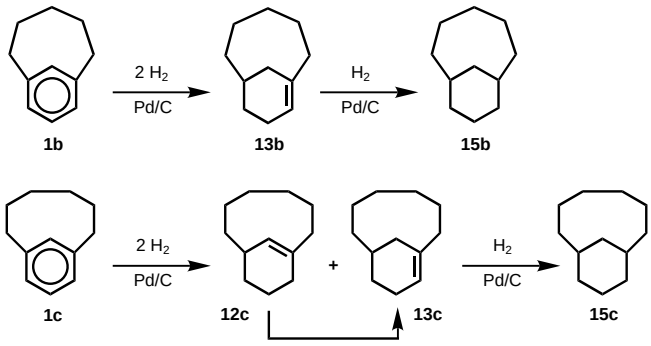
were available in limited quantities only, it seemed not feasible to determine the heat of hydrogenation quantitatively employing a conventional calorimeter. Therefore, we used a special hydrogenation calorimeter which has proven to yield results as accurate as other calorimeters, but which requires samples of not more than a few milligrams.[17, 22] The molar heat of hydrogenation is derived from the ratio between the heat released during hydrogenation of the compound under investigation and that of a reference compound (styrene or 1-hexene) for which the molar heat of hydrogenation has been firmly established.[23] The results of these measurements are listed in Table 1.

Table 1. Enthalpies of hydrogenation of [*n*]metacylophanes **1**.

Compound	Replicates	Catalyst	Molar ratio	mg per injection	$-\Delta H^{hyd}_{298}$ [kJ mol^{-1}]
1b	9	Pd	1.73[a]	2.39	220.1 ± 2.5
1b	9	Pt	1.53[b]	2.39	251.5 ± 4.6
1c	8	Pd	1.18[a]	1.98	138.9 ± 2.5
1c	9	Pd	1.18[a]	3.97	143.1 ± 3.8
1c	8	Pt	1.64[b]	1.98	174.1 ± 3.8

[a] Moles of styrene per moles of **1**. [b] Moles of 1-hexene per moles of **1**.

Bearing in mind that **1b** is a strained compound, it was expected that its heat of hydrogenation would be larger than that of benzene. From Table 1, it follows that this is qualitatively correct, but the differences were much smaller than predicted. A rough estimate for the heat of hydrogenation of **1b** may be deduced as follows: adding the calculated strain energy of **1b** (174 kJ mol^{-1})[10] to the heat of hydrogenation of benzene (208 kJ mol^{-1})[11] leads to a value of 382 kJ mol^{-1}. The actual value will be lower as the strain in **1b** is not fully released in the bicycloalkane **15b** (Scheme 5). However, the very large discrepancy between the estimated value (382 kJ mol^{-1}) and the experimental one (220 kJ mol^{-1}) cannot be due to the residual strain in **15b** alone; it strongly pointed to incomplete hydrogenation.



Scheme 5. Hydrogenation of **1b** and **1c**.

This assumption was corroborated by the shape of the temperature curves. These shapes varied depending on the catalyst. The curve which is normally observed for palladium-catalysed hydrogenations is shown in Figure 2a. Preceding the injection of the sample, the temperature of the calorimeter slowly declines towards that of the environment. Injection of the sample results in an immediate temperature jump caused by the heat of hydrogenation (about 10 s); this is followed again by a gradual temperature decline.

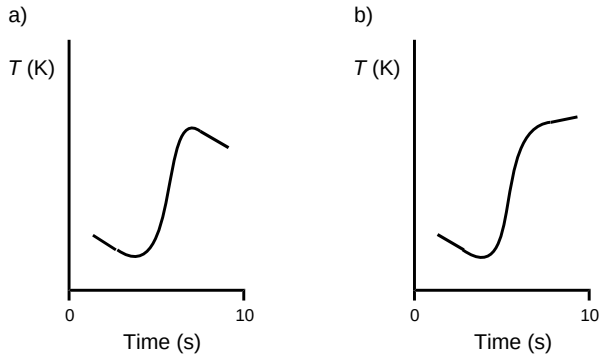


Figure 2. Thermogramm for hydrogenation of **1b** and **1c**; a) with 5% palladium on charcoal, b) with 5% platinum on charcoal.

When a Pt catalyst was used, the curves were different. After the sharp initial rise of the temperature a more gradual temperature increase followed (Figure 2b). This went along with a substantially higher heat of hydrogenation (252 kJ mol^{-1}) which, however, cannot be quantitatively evaluated because of the slow rate of this conversion. These observations indicated a second but slower heat generating reaction, presumably an additional hydrogenation step.

The reliability of the values for the heat of hydrogenation obtained for **1b** and **1c** by calibration with an absolute standard was confirmed through measurement of the relative values obtained by alternating injection of the two compounds. This experimentally determined ratio (1.593) was close to that obtained by dividing the values in Table 1 ($\frac{220}{141}=$ 1.560), but again, it strongly exceeded the value estimated from strain considerations as described above for **1b** ($\Delta H(\mathbf{1b}):\Delta H(\mathbf{1c})=\frac{382}{329}=1.161$).

Isolation and characterisation of (hyperstable) bridgehead olefins: To support the hypothesis of partial hydrogenation, we performed a product analysis. Care was taken to mimic the environment and reaction conditions in the calorimeter as closely as possible. In a typical experiment, 100 mg of a 10% solution of **1** was injected into a one-neck round-bottomed flask containing a slurry of 10% palladium on charcoal in *n*-hexane at a hydrogen pressure of 1 atm. The reaction was allowed to proceed for a certain period of time, after which the catalyst was rapidly filtered off by suction filtration through a glass frit. The filtrate was concentrated under reduced pressure and analysed by GLC and by ^{1}H-NMR spectroscopy. We were excited to discover that even after 1 min of hydrogenation (note that the calorimetric measurements take about 10 s), the reaction product contained a partially reduced compound (characterised by GC-MS) besides the expected fully saturated bicyclo[5.3.1]undecane (**15b**) (Scheme 5). On the basis of its mass and of an olefinic resonance at $\delta = 5.38$ (t, ^3J(H,H) = 7.6 Hz), the former was identified as the bridgehead olefin **13b**. In the ^{13}C-NMR spectrum, the corresponding olefinic carbon appeared at $\delta =$ 121.0. Extension of the reaction time resulted in a slow conversion; after 5 min only **15b** was detected. Hydrogena-

0947-6539/00/0609-1540 $ 17.50+.50/0 *Chem. Eur. J.* **2000**, *6*, No. 9

tion of **1c** showed a similar picture, although in this case, besides bicyclo[6.3.1]dodecane (**15c**), *two* partially reduced compounds were identified. The ^{1}H-NMR spectrum revealed two olefinic resonances at $\delta = 5.39$ (t, $^3J(H,H) = 7.7$ Hz) and 5.29 (br s), which were assigned to **13c** and **12c**, respectively.

The results collected in Table 2 suggest that the primary product formed from **1c** is the *trans*-cyclononene **12c**. This is surprising as **13 c**, with its bridgehead double bond *trans* in an eleven-membered ring, will undoubtedly be more stable than **12 c** where the double bond is *trans* in a nine-membered ring. In this context the following interesting phenomenon is worth mentioning. While **1c** has been completely consumed after less than 1 min, the molar fraction of **13c** initially increases at the expense of **12c** as the hydrogenation proceeds (Table 2).

Table 2. Product composition (%) on hydrogenation of **1** as a function of the reaction time.

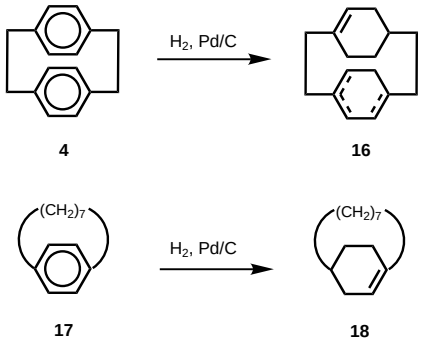
Entry	Compound	Reaction time [min]	Products[a]		
1	**1b**	1		**13b** (54.7)	**15b** (45.3)
2	**1b**	2		**13b** (19.9)	**15b** (80.1)
3	**1b**	5		**13b** (0)	**15b** (100)
4	**1c**	1	**12c** (73.9)	**13c** (26.1)	**15c** (0)
5	**1c**	2	**12c** (54.0)	**13c** (31.1)	**15c** (14.9)
6	**1c**	5	**12c** (8.4)	**13c** (48.5)	**15c** (43.1)
7	**1c**	60	**12c** (0)	**13c** (0)	**15c** (100)

[a] Product composition based on GC-MS measurements.

This observation suggests that **12c** is isomerised to **13c**, thus confirming the greater stability of the latter (vide infra). The fast migration of a double bond in bridged medium rings into the hyperstable bridgehead position in the presence of acids or hydrogenation catalysts has been documented recently.[24] However, one should be cautious in relating the reactivity of a compound to its stability. For instance, hydrogenation studies on alkyl substituted naphthalenes have demonstrated that the rate of hydrogenation and hence product formation strongly depend on steric factors;[25] this is not surprising because the double bond to be hydrogenated has to get into close contact with the surface of the catalyst. Thus, it seems justified to assume that hydrogenation of an anti-Bredt type double bond as in **1c** with its non-planar environment will be retarded because interaction with the catalyst will be hampered by stronger steric repulsion. As a result the thermodynamically less stable **12c** is formed as the primary product. It is also noteworthy that **13c** is hydrogenated more slowly than **13b**; after 5 min, **13b** was completely reduced to **15b**, while 50% **13c** survived.

On the one hand, the unexpected formation of partly hydrogenated intermediates was a counterblow for our primary goal to determine the strain energy of **1** directly, but we did arrive at a partial solution of this problem (vide infra). On the other hand, both the extremely high reactivity of **1** under mild conditions (palladium on charcoal, 1 atm H_2) and the identification of olefinic intermediates which react more slowly than the *aromatic* starting material, gave a new and rewarding direction to our investigations.

Formation of olefins from cyclophanes has previously been observed in a few cases. Hydrogenation of [2.2]paracyclophane (**4**) resulted in the formation of a mixture of three dienes **16** which could be forced to undergo further hydrogenation only under much more severe reaction conditions (Scheme 6).[26] Similarly, hydrogenation of [7]paracyclophane (**17**) afforded **18**[27]; the extraordinary stability of **18** was attributed to its so-called hyperstability.



Scheme 6. Partial hydrogenation of **4** and **17**.

The concept of hyperstability was first coined by Schleyer in 1981.[28] According to this definition, hyperstable olefins are less strained than the corresponding hydrogenated species.[29] This is expressed by a negative value for the olefinic strain (OS) which is defined as the strain of the lowest energy conformer of the olefin minus the strain of the lowest energy conformer of the hydrogenated compound. For bridgehead olefins derived from [n]paracyclophanes, the highest degree of hyperstability ($OS = -58.6$ kJ mol^{-1}) was found for **18**.[28] In order to address the question whether **13b** and **13c** belong to this rare class of compounds, we have conducted a theoretical study.

Calculations

Geometric parameters: To obtain a starting geometry for the DFT calculations, the structures of all compounds under investigation were optimised by the MM3 method as implemented in the Alchemy 2000 program.[30] In most cases, several conformers only slightly differing in energy were located. Normally, only the lowest energy conformers were evaluated with the DFT method as implemented in the ADF program (version 2.3.6),[31] except when the MM3 derived energy difference between two conformations was less than 4 kJ mol^{-1}. All data in Scheme 7 and Table 3 refer to the lowest energy conformers. Both the MM3 values and parameters obtained by the hybrid DFT/HF method at the B3LYP/6-31G*[32] level of theory have been added. These merely serve to place the DFT results in perspective. In the discussion we will mainly focus on the DFT results which permit a fair comparison to earlier DFT calculations on **1a** and **1b**.[10]

In order to evaluate the accuracy of the DFT method, *trans*-cyclooctene (**19**) was considered as a test-case. The bending of the olefin moiety can be expressed by the dihedral or torsion angle Θ of the two carbon atoms attached to the double bond which are part of the bridge.[33–36] For **19** the calculated angle Θ (137.8°) was found to correspond closely to that experimentally determined in a crystalline derivative (137.7°).[33] It

Table 3. Calculated strain energy (SE) and olefinic strain (OS).[a, b]

Compound	MM3[c] SE	MM3[c] OS	DFT[d] SE	DFT[d] OS	B3LYP/6–31G*[e, f] SE	B3LYP/6–31G*[e, f] OS
12a	142.8	72.4	152.4	100.8	160.0	107.4
12b	103.2	27.9	92.7	33.2	95.1	33.8
12c	91.6	–1.0	84.6	8.7	86.2	7.9
13a	82.2	11.8	61.1	9.4	64.0	11.5
13b	77.2	1.8	64.8	5.3	65.3	3.1
13c	74.4	–18.2	63.7	–12.1	66.1	–12.2
14a	48.9	–21.6	35.7	–16.0	35.5	–17.0
14b	67.5	–7.8	54.2	–5.4	56.2	–5.0
14c	84.1	–8.5	69.7	–6.1	71.5	–6.8
15a	70.5	–	51.7	–	52.5	–
15b	75.4	–	59.5	–	61.3	–
15c	92.6	–	75.9	–	78.4	–
19	–	–	80.9	27.9	–	–
20	–	–	53.0	–	–	–

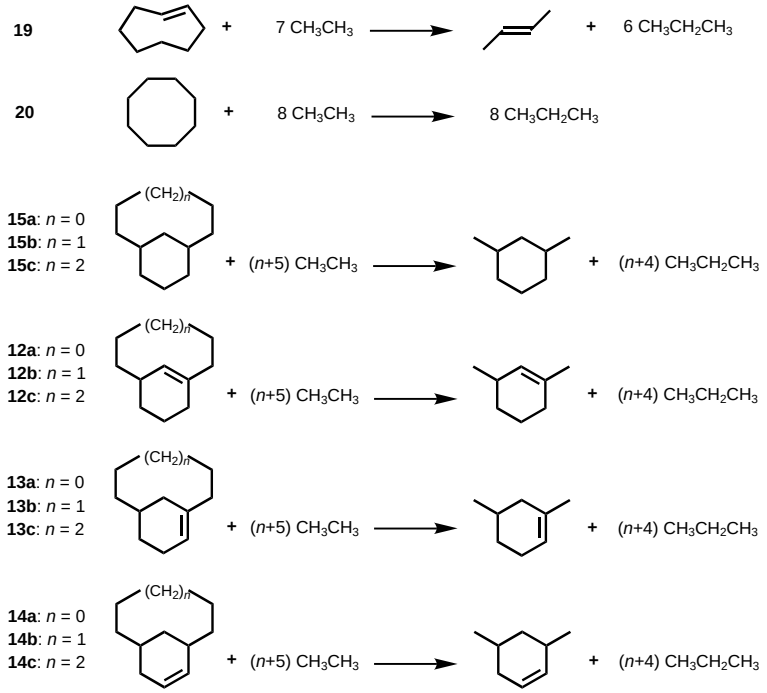
[a] Energies in kJ mol^{-1}. [b] All calculations refer to the lowest energy conformers. [c] Ref. [30]. [d] Ref. [31]. [e] Ref. [32]. [f] $\Delta E^0+\Delta ZPE^0$.

should be noted that despite the structural differences, the value of Θ calculated for **12b** (138.2°) is very close to that of **19**. The effect of ring size on distortion is illustrated by the decrease along the series **12a** ($\Theta = 119.3°$), **12b** ($\Theta = 138.2°$) and **12c** ($\Theta = 160.8°$). A similar, though less pronounced trend is observed for the series **13a** (158.1°), **13b** (170.3°) and **13c** (169.9°). Only **13a** displays a marked degree of distortion; **13b** and **13c** are, in this regard, comparable to analogous unstrained olefins.

Strain energies and olefinic strains:[28, 29, 34, 35, 37] Again *trans*-cyclooctene (**19**) was first considered as a test-case. Its strain energy (SE) was evaluated by calculating the energy released in a homodesmotic reaction (Scheme 7); a SE of 80.9 kJ mol^{-1} and an olefinic strain (OS) of 27.9 kJ mol^{-1} were obtained. The latter value may appear rather low, but this is mainly a consequence of the relatively large SE of cyclooctane (**20**) (53 kJ mol^{-1}); this value is in good agreement with the experimental one derived from heat of combustion measurements (40.2 kJ mol^{-1}).[38]

It should be mentioned that strain in medium-sized rings is to a large extent caused by eclipsing and transannular repulsion between methylene groups, and thus may be expected to increase along with their number (until, in large rings, strain-free conformations become available). The energy difference between *cis*- and *trans*-cyclooctene (45.1 kJ mol^{-1}) fits nicely with the experimental difference between the molar heats of hydrogenation of these compounds (47.6 kJ mol^{-1}).[12] These results give confidence that the DFT method is indeed capable of reliably predicting the strain energy of olefins.

The SE of **12b** (Table 3, SE = 92.7 kJ mol^{-1}, OS = 33.2 kJ mol^{-1}) was found to be close to that of **19** (SE = 80.9 kJ mol^{-1}, OS = 27.9 kJ mol^{-1}, which is not surprising considering that both compounds are *trans*-cyclooctenes. On going to **12a**, the SE increases dramatically (SE = 152.4 kJ mol^{-1}, OS = 100.8 kJ mol^{-1}),[39] whereas enlargement of the ring leads to a reduction of the SE in **12c** (SE = 84.6 kJ mol^{-1}, OS = 8.7 kJ mol^{-1}). For analogous reasons as indicated for medium-sized cycloalkanes (vide supra), the SE is indeed found to increase from **15a** (51.7 kJ mol^{-1}) to **15c** (75.9 kJ mol^{-1}). A similar picture emerges for **13a**, **13b** and **13c**. However, the SE is considerably lower than for the "anti-Bredt" series **12**. As a result, a boundary line is encountered between **13b** (OS = 5.3 kJ mol^{-1})[40] and the hyperstable **13c**, for which a (slightly) negative value was found (OS = –12.1 kJ mol^{-1}).

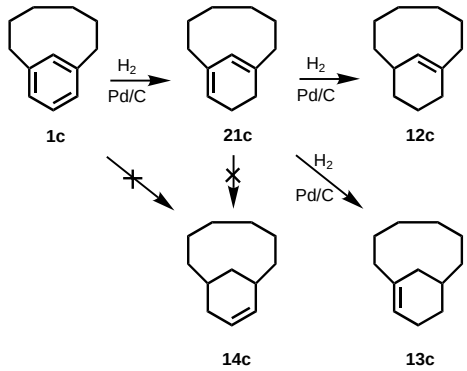


Scheme 7. Different olefins investigated, see Table 3. All attachments to six-membered rings (substituents and bridges) are *cis*.

The calculated additional stability of **13c** compared with **13b** correlates with its greater reluctance to undergo hydrogenation. The outcome of the calculations for **13b** may seem surprising because it is predicted not to be hyperstable, yet it survived for about 50% after 1 min of hydrogenation whereas even after 10 s, the cyclophane **1b** had completely disappeared. This implies that **1b** and **1c** are as reactive as a normal (unstrained) olefin. In contrast, the olefins **14** (which have a *dialkyl*-substituted double bond!) are all predicted to be hyperstable, but nevertheless, they were not detectable in the hydrogenation experiments. MM3 calculations on the monoenes **12c**, **13c** and **14c** gives the sequence of their heat of formation as **14c** ($\Delta H^f_{298} = -36.1$ kJ mol^{-1}) > **12c** ($\Delta H^f_{298} = -37.5$ kJ mol^{-1}) > **13c** ($\Delta H^f_{298} = -55.3$ kJ mol^{-1}). The reason why

0947-6539/00/0609-1542 $ 17.50+.50/0 Chem. Eur. J. 2000, 6, No. 9

14c is not observed may thus be a thermodynamic one, and this isomer is either not formed at all or it is rapidly isomerised to **13c**; note that this thermodynamic argument does not hold for **14b** ($\Delta H^{f}_{298} = -28.9$ kJ mol^{-1}) which is as stable as **13b** ($\Delta H^{f}_{298} = -28.7$ kJ mol^{-1}). Alternatively, one might be tempted to ascribe the absence of **14** to the influence of steric factors on the rate of hydrogenation mentioned above; in view of the lower degree of substitution of **14**, they may be expected to bind more efficiently to the surface of the catalyst, and thus be hydrogenated more rapidly. However, this rationalisation is not in line with the observation that **15**, the hydrogenation product of **14**, was not detectable after $t = 1$ min in the case of **15c**. Even for **15b**, extrapolation of the values of Table 2 to $t = 10$ s gives a maximum amount of **15b** of less than 10%. So presumably, **14** are not formed at all, and we suggest that this is due to kinetic factors because, as described for **1c** in Scheme 8, the primary addition of H_2 will occur at the "lower half" of the benzene ring of **1c** to furnish **21c** because on approach of **1** to the catalyst surface, this position suffers less from steric hindrance.



Scheme 8. Hydrogenation of **1c**.

*Evaluation of the thermochemistry of **1***: Two closely related questions have so far remained unanswered: In what perspective do we have to place the thermochemical data, and secondly, to what extent are the DFT methods able to reproduce the experimental data? In order to address these questions, both the hydrogenation energies of **1b** and **1c** were evaluated by the DFT method which gave a value of $\Delta E = -238$ kJ mol^{-1} for the hydrogenation of **1b** to **13b** (Table 4).

Although this appears to be in reasonable agreement with the experimental value ($\Delta H^{hyd}_{298} = -220.1$ kJ mol^{-1}) at first glance, it should be stressed that the calculated value relates to the gas-phase at 0 K. Inclusion of zero-point energies (ΔZPE), thermal corrections and a correction term for the work associated with the loss of two moles of gas (H_2) reduces the exothermicity considerably ($\Delta H^{hyd}_{298} = -182$ kJ mol^{-1}), but to such an extent that it now turns out to be much lower than the experimental value ($\Delta\Delta H^{hyd}_{298} = 38$ kJ mol^{-1}). For the hydrogenation of **1c** leading to **12c** or **13c**, values of $\Delta H^{hyd}_{298} = -113$ and -132 kJ mol^{-1}, respectively, were calculated. Again the calculated value for the hydrogenation to give **12c** as the primary hydrogenation product differs about 28 kJ mol^{-1} from the experimental one. Calculations at the B3LYP/6-31G* level afford comparable results; for the hydrogenation of **1b** and **1c** to give **13b** and **12c**, respectively, values of $\Delta H^{hyd}_{298} = -186$ and -109 kJ mol^{-1}, were found, clearly much smaller than the experimental values.

Table 4. Heats of hydrogenation.[a]

Reaction	MM3[b]	DFT[c, d, e]	B3LYP/6–31G*[e, g, g]	exptl[g]
1b → **13b**	−172.1	−182.1	−186.0	−220.1 ± 2.5
1c → **12c**	−115.1	−113.1	−109.4	−141.0 ± 2.5
1c → **13c**	−132.9	−132.0	−128.0	
13b → **15b**	−115.0	−115.6	−114.5	
12c → **15c**	−112.6	−113.9	−116.5	
13c → **15c**	−94.9	−96.2	−97.9	

[a] Energies in kJ mol^{-1}. [b] Ref. [30]. [c] Ref. [31]. [d] $\Delta H^{298} = \Delta E^{298} + \Delta ZPE$ (B3LYP/6–31G*)$^{298} + \Delta(PV)$. [e] ZPEs are scaled by 0.96, Ref. [41]. [f] Ref. [32]. [g] This work.

To assess the origin of these large discrepancies, we have evaluated the hydrogenation enthalpy of the reference system benzene to give cyclohexene followed by hydrogenation to cyclohexane. For the overall reaction, a value of 193.6 kJ mol^{-1} is obtained, clearly less than the experimental value (208 kJ mol^{-1}).[11, 14, 15] The error becomes even larger for the hydrogenation of *m*-xylene to give 1,3-dimethylcyclohexane (calcd 174 kJ mol^{-1}, exptl[11] 202 kJ mol^{-1}). However, the calculated reaction enthalpy for the hydrogenation of cyclohexene (116 kJ mol^{-1}) nicely matches with experiment (120 kJ mol^{-1}). Therefore, we are bound to conclude that both DFT methods overestimate the aromatic resonance stabilisation. The evaluated error for *m*-xylene (28 kJ mol^{-1}) is similar to the one observed for **1b** and **1c** (vide supra), and it comprises essentially the difference between theory and experiment for the first two hydrogenation steps. Similar discrepancies have been pointed out before.[41, 42] Interestingly, the error involved in the MM3 calculations is comparable.

As stated above, both DFT methods do reproduce the experimental hydrogenation enthalpy of cyclohexene very accurately, which gives confidence that this also applies for other olefins. We were thus encouraged to rely on the calculated heats of hydrogenation of **13b** and **12c** (−115.6 and −113.9 kJ mol^{-1}). Combining these calculated with the experimental values for the transformation of **1b** to **13b** and **1c** to **12c** provides the heats of hydrogenation for the complete conversion of **1b** to **15b** (−335.7 kJ mol^{-1}) and of **1c** to **15c** (−254.9 kJ mol^{-1}). If we account for the residual strain in **15b** and **15c**, these values become −395.2 kJ mol^{-1} and −330.8 kJ mol^{-1}, respectively. These numbers directly relate to the strain energies of **1b** and **1c**; subtraction of the heat of hydrogenation of benzene (−208 kJ mol^{-1}) affords strain energies of 187 and 123 kJ mol^{-1} for **1b** and **1c**, respectively, in satisfactory agreement with the SEs derived by DFT calculations on homodesmotic reactions (174 and 121 kJ mol^{-1}).[10]

Conclusion

Although we have not attained our initial goal to experimentally determine the SE of **1a** and **1b** directly, we have been able to obtain values which are composed of an experimen-

tally determined part, comprising the major part of the strain energy, and a part derived from DFT calculations.

In addition, these experiments have provided us with experimental results which were used to assess the accuracy of the DFT calculations. These turned out to be satisfactory for most purposes, that is the calculation of strain energies and hydrogenation enthalpies of olefins, but failed to fully reproduce the hydrogenation enthalpies of (substituted) benzenes.

Finally, a rewarding spin off was the identification of the kinetically stable olefins **12c**, **13b** and **13c** which are hydrogenated more slowly than their aromatic precursors **1b** and **1c**; this once more testifies to the extraordinary influence of strain on the reactivity of aromatic compounds.

Experimental Section

General: ^{1}H-NMR spectra were referenced to $CHCl_3$ ($\delta = 7.27$), ^{13}C-NMR spectra to $CDCl_3$ ($\delta = 77.0$). For ^{13}C-NMR spectra recorded in the ^{1}H-decoupled mode, carbon multiplicities were assigned on the basis of APT experiments. GC-MS spectra were recorded on a HP-5971-MSD apparatus. High-resolution mass spectrometry (HR-MS) was performed on a Finnigan MAT-90 mass spectrometer operating at an ionisation potential of 70 eV. Melting points were measured on samples in unsealed capillary tubes and are uncorrected. Microanalyses were performed by Microanalytisches Labor Pascher. Preparative gas chromatography was performed on a Intersmat P120 apparatus equipped with a 1.5 m 15% SE-30 on Chromosorb W 60/80 mesh column and H_2 as carrier gas. All reagents and solvents are commercially available and have been purchased from either Acros or Aldrich. DMSO was distilled from CaH prior to use and stored over molecular sieves (4 Å).

Synthesis: The synthesis of **7b** and **7c** has been described previously.[43]

***endo*-11-Bromo-*endo*-9-*exo*-11-dichlorotricyclo[5.3.1.0]undecane (8b′)**: *t*BuOK (33.8 mmol, 3.78 g) was added over a period of 6 h at 0 °C under nitrogen using a solid addition tube to a solution of **7b** (15.0 mmol, 2.55 g) and $CHBr_2Cl$ (37.5 mmol, 7.76 g) in dry benzene (70 mL). During the addition the solution turned from colourless to yellow. The reaction mixture was stirred for an additional 18 h at RT after which $CHBr_2Cl$ (37.5 mmol, 7.76 g) was added followed by the slow (6 h) addition of another portion of *t*BuOK (33.8 mmol, 3.78 g) at 0 °C. Again the reaction mixture was stirred for 18 h at RT. This procedure was repeated once more to ensure a conversion ratio > 90%. Subsequently, the reaction mixture was partitioned between pentane and water, the layers were separated, and the water layer was extracted three times with pentane. The combined organic layers were washed with water (3 ×) dried on $MgSO_4$ and concentrated at reduced pressure to afford a yellow oil. At this stage ^{1}H NMR indicated a conversion rate of about 95%. The crude product was purified by column chromatography on silica gel (eluent pentane) to give a colourless oil consisting of **8b**, **8b′** and a small fraction of **9b**. This mixture was dissolved in $CHCl_3$ to which a few drops of water had been added and stirred for three days during which **8b** and **9b** were fully converted into **10b**. After evaporation of the solvent the remaining dark brown oil was subjected to column chromatography (silica gel/pentane) to give nearly pure **8b′** as a colourless oil. Further purification was achieved by crystallisation from pentane at −20 °C to give **8b′** as colourless needles (0.98 g, 3.30 mmol, 22%). M.p.: 81–83 °C; ^{1}H NMR (200.13 MHz, $CDCl_3$, 298 K): $\delta = 4.25$ (X-part of A_2B_2X-system, $^3J(H,H) = 8.1$ Hz, 4.1 Hz, 1H), 2.66 (AB-part of A_2B_2X-system: $\delta_A = 2.86$ ($^2J(H,H) = -16.0$ Hz, $^3J(H,H) = 8.1$ Hz, 2H), $\delta_B = 2.46$ ($^2J(H,H) = -16.0$ Hz, $^3J(H,H) = 4.1$ Hz, 2H), 2.15–1.60 (m, 9H), 1.22 (m, 1H); ^{13}C{^{1}H} NMR (50.32 MHz, $CDCl_3$, 298 K): $\delta = 69.1$ (s, C11), 58.6 (d, C9), 47.1 (t, C(8,10)), 44.3 (s, C(1,7)), 33.5 (t, 2C), 32.4 (t, C4), 26.9 (t, 2C); MS (70 eV): *m*/*z* (%): 298 (3.0) $[M]^+$, 263 (18.0) $[M - Cl]^+$, 242 (100) $[M - C_4H_8]^+$, 217 (71.9) $[M - Br]^+$, 145 (61.3); HR-MS: $C_{11}H_{15}{}^{79}Br^{35}Cl_2$ $[M]^+$ calcd 295.97343, found 295.97352 ± 0.0001; $C_{11}H_{15}BrCl_2$: calcd C 44.33, H 5.08, Cl 23.79; found C 44.83, H 5.16, Cl, 24.5.

***endo*-12-Bromo-*endo*-10-*exo*-12-dichlorotricyclo[6.3.1.0]dodecane (8c′)**: **8c′** was synthesised from **7c** following a similar procedure as described for **8b′**. However, some slight adaptations were made in this specific case. It turned out that during column chromatography **8c** had almost completely been converted into **10c** as indicated by ^{1}H NMR. Crystallisation of the white solid obtained after chromatography from pentane at −20 °C afforded **8c′** of sufficient purity (4.4 mmol, 1.37 g, 22%). M.p.: 92–94 °C; ^{1}H NMR (200.13 MHz, $CDCl_3$, 298 K): $\delta = 4.26$ (X-part of A_2B_2X-system, $^3J(H,H) = 8.5$ Hz, 5.6 Hz, 1H), 2.57 (AB-part of A_2B_2X-system: $\delta_A = 2.60$ ($^2J(H,H) = -16.4$ Hz, $^3J(H,H) = 8.5$ Hz, 2H), 2.55 ($^2J(H,H) = -16.4$ Hz, $^3J(H,H) = 5.6$ Hz, 2H), 1.94–1.87 (m, 2H), 1.57–1.41 (m, 10H); ^{13}C NMR (50.32 MHz, $CDCl_3$, 298 K): $\delta = 66.45$ (s, C12), 56.81 (d, $^1J(C,H) = 159$ Hz, C10), 43.42 (t, $^1J(C,H) = 133$ Hz, C(9,11)), 41.39 (s, C(1,8)), 28.34 (t, 2C), 25.53 (t, 2C), 25.10 (t, 2C); MS (70 eV): *m*/*z* (%): 238 (18.8) $[M - Br]^+$, 182 (13.0), 159 (41.6), 130 (100.0), 117 (57.4); HR-MS: $C_{12}H_{17}{}^{79}Br^{35}Cl_2$ $[M]^+$ calcd *m*/*z* 309.98908, found 309.98905 ± 0.0001; $C_{12}H_{17}BrCl_2$: calcd C 46.18, H 5.49, Cl 22.72; found C 46.66, H 5.74, Cl 23.7.

***endo*-10-*exo*-12-Dichlorotricyclo[6.3.1.0]dodecane (6c′)**: A solution of **8c′** (0.25 mmol, 78 mg) and triphenyltin hydride (0.275 mmol, 96 mg) in dry diethyl ether (20 mL) was heated for 3 h under reflux. The solution was allowed to cool down to RT and the solvent was removed in vacuo. The residue was purified by column chromatography to give **6c′** as a white solid which could be crystallised from pentane at −20 °C to give colourless needles (48 mg, 0.21 mmol, 83%). M.p. 77–79 °C; ^{1}H NMR (200.13 MHz, $CDCl_3$, 298 K): $\delta = 3.87$ (X-part of AA′AA′X system, apparent quintet, virtual $^3J(H,H) = 8.6$ Hz (weak higher order effects), 1H), 2.88 (s, 1H), 2.24 (AA′AA′-part of AA′AA′X system, apparent d, virtual $^3J(H,H) = 8.6$ Hz (weak higher order effects), 4H), 1.75 (m, 2H), 1.58–1.54 (m, 6H), 1.46–1.40 (m, 4H); ^{13}C NMR (50.32 MHz, $CDCl_3$, 298 K): $\delta = 53.57$ (d, $^1J(C,H) = 152$ Hz C10), 43.87 (d, $^1J(C,H) = 186$ Hz, C12), 41.38 (t, $^1J(C,H) = 134$ Hz, C9,C11), 32.92 (s, C1,C8), 25.31 (t, $^1J(C,H) = 123$ Hz, 2C), 24.49 (t, $^1J(C,H) = 127$ Hz, 2C), 23.90 (t, $^1J(C,H) = 127$ Hz, 2C); MS (70 eV): *m*/*z* (%): 232 (9.6) $[M]^+$, 197 (85) $[M - Cl]^+$, 162 (97.6) $[M - Cl_2]^+$, 91 (100.0); HR-MS: $C_{12}H_{18}{}^{35}Cl_2$ $[M]^+$ calcd 232.07856, found: 232.07850 ± 0.0001; $C_{12}H_{18}Cl_2$: calcd C 61.81, H 7.78, Cl 30.41; found C 61.63, H 7.74, Cl 30.2.

[5]Metacyclophane (1b): A solution of **8b′** (614 mg, 2.06 mmol) in DMSO (75 mL) was added under nitrogen at 35 °C over a period of 2 h to a solution of *t*BuOK (20.0 mmol, 2.24 g) in dry DMSO (50 mL). The reaction mixture was stirred for another 3 h at 35 °C during which the colour changed to deep black. Subsequently, the reaction mixture was poured into a mixture of pentane (100 mL) and ice water (200 mL). The layers were separated and the water layer was extracted three times with pentane (100 mL). The combined organic layers were washed with water (3 × 100 mL), brine (1 × 100 mL), dried on $MgSO_4$ and concentrated at reduced pressure. The remaining yellow oil was purified by flash column chromatography, to yield **1b** as a slightly yellow oil (240 mg, 1.65 mmol, 80%). All spectroscopic data (^{1}H NMR[4] and ^{13}C NMR[44]) are consistent with those previously reported.

[6]Metacyclophane (1c): **1c** was prepared from **8c′** by a procedure similar to that described for **1b**. However, the reaction mixture was stirred for 18 h at RT instead of 3 h at 35 °C. From ^{1}H-NMR and GC-MS data it was concluded that the crude reaction product consisted of a mixture of **1c** (70%), 12-chloro[6]metacyclophane (**1c-Cl**) (20%) and 12-bromo[6]metacyclophane (**1c-Br**) (10%). Separation could be achieved by preparative GLC.

Alternatively, **1c** was prepared from **6c′**. *t*BuOK (90.0 mg, 0.804 mmol) was added under nitrogen at RT to a solution of **6c′** (20.43 mg, 0.0881 mmol) in dry DMSO (5.0 mL). The resulting mixture was stirred for 18 h at RT, and then poured into a mixture of pentane (10 mL) and ice-water (20 mL). The layers were separated and the water layer was extraced three times with pentane. The combined organic layers were washed with water (3 ×), brine (1 ×), dried over $MgSO_4$ and concentrated at reduced pressure to yield **1c** as a colourless oil (12.43 mg, 0.0777 mmol, 88%). The ^{1}H-NMR spectrum is consistent with that previously reported.[45] ^{13}C NMR (50.32 MHz, $CDCl_3$, 298 K): $\delta = 143.3$ (s, C7,C11), 134.9 (d, C12), 128.4 (d, C9), 124.0 (d, C8,C10), 34.5 (t, 2C), 33.1 (t, 2C), 27.7 (t, 2C); MS (70 eV): *m*/*z* (%): 160 (55.7) $[M]^+$, 145 (37.9), 131 (40.7), 117 (42.2), 104 (100.0), 91 (60.6).

Hydrogenation of 1b and 1c: The system used consisted of a one-neck round bottomed flask fitted with a rubber septum, through which a needle was stuck by which hydrogen was introduced from a constant pressure

0947-6539/00/0609-1544 $ 17.50+.50/0 *Chem. Eur. J.* **2000**, *6*, No. 9

source (1 atm). The flask contained a slurry of 10% palladium on charcoal (200 mg) in *n*-hexane which was saturated with hydrogen. A solution of **1b** or **1c** (100 mg of an approximately 10% solution in *n*-hexane) was then injected and allowed to react for a distinct period of time (1 to 60 min). The reaction mixture was than rapidly filtered through a glass frit by suction filtration. The filtrate was concentrated at reduced pressure and the remaining oil was analysed by ^{1}H NMR and GC-MS.

Bicyclo[5.3.1]undec-1(10)-ene (13b): Complete characterisation of **13b** has not been accomplished. Only the most revealing data are reported. ^{1}H NMR (200.13 MHz, $CDCl_3$, 298 K): $\delta = 5.38$ (t, ^3J(H,H) = 7.6 Hz, 1H; olefinic); ^{13}C NMR (50.32 MHz, $CDCl_3$, 298 K): $\delta = 121.0$ (d, 1C); MS (70 eV): *m*/*z* (%): 150 (58.2) $[M]^+$ 135 (47.5), 121 (43.9), 108 (52.4), 93 (52.6), 79 (100.0).

Bicyclo[5.3.1]undecane (15b): All spectroscopic data (^{1}H NMR, ^{13}C NMR and GC-MS) are consistent with those previously reported.[46]

Bicyclo[6.3.1]dodec-1(12)-ene (12c): Complete characterisation of **12c** has not been achieved. Only the most revealing data are reported here. ^{1}H NMR (200.13 MHz, $CDCl_3$, 298 K): $\delta = 5.29$ (br s, 1H; olefinic); MS (70 eV): *m*/*z* (%): 164 (26.6) $[M]^+$, 149 (2.9), 135 (11.8), 121 (100.0).

Bicyclo[6.3.1]dodec-1(10)-ene (13c): Complete characterisation of **13c** has not been achieved. Only the most revealing data are reported. ^{1}H NMR (200.13 MHz, $CDCl_3$, 298 K): $\delta = 5.39$ (t, ^3J(H,H) = 7.7 Hz, 1H; olefinic); MS (70 eV): *m*/*z* (%): 164 (41.5) $[M]^+$, 149 (7.9), 135 (17.3), 121 (100.0).

Bicyclo[6.3.1]dodecane (15c): Due to the small scale on which the hydrogenation experiments were carried out, **15c** was not available in sufficient quantities for complete analysis. ^{1}H NMR (200.13 MHz, $CDCl_3$, 298 K): $\delta = 2.03$ (d, ^2J(H,H) = −14.2 Hz, 1H), 1.87–1.19 (m, 21H); ^{13}C NMR (50.32 MHz, $CDCl_3$, 298 K): $\delta = 34.63$ (d, C1,C8), 33.32 (t, 2C), 32.90 (t, 2C), 30.39 (t, 1C), 28.72 (t, 2C), 28.56 (t, 2C), 17.16 (t, 1C); MS (70 eV): *m*/*z* (%): 166 (24.0) $[M]^+$, 138 (9.5), 124 (9.0), 96 (71.7), 81 (87.3), 67 (100.0).

Thermochemistry: The calorimeter has been described previously.[22] Known weights of standard solutions of styrene or 1-hexene and an [n]metacyclophane were hydrogenated under conditions that were made as nearly identical as possible, using either 5% palladium on charcoal or 5% platinum on charcoal as a catalyst (both from Aldrich). The ratio of the reaction heats leads to the molar enthalpy of hydrogenation (ΔH^{hyd}_{298}) of the unknown, assuming ΔH^{hyd}_{298}(styrene) to be -118.0 kJ mol^{-1}[23a] or ΔH^{hyd}_{298}(1-hexene) to be -126.6 kJ mol^{-1}.[23b]

The metacylophanes were available as 13–16% solutions in *n*-hexane. Depending on the molecular weight of the cyclophane and its expected ΔH^{hyd}_{298}, 37 to 42 mg of standard were weighed to approximately 2 μg on a Sartorius electronic microbalance[47] and diluted with *n*-hexane to 500 μL in a thin-walled, calibrated tube of 4.5 mm inside diameter. Samples and solvent (*n*-hexane) were handled using microliter syringes.

The styrene or 1-hexene standard was made up so that it produced approximately the same amount of heat (to within 10%) upon hydrogenation as the unknown solution. Aliquot 20 μL portions of the standard and sample were injected into the calorimeter using a GLC microsyringe, fitted with a Cheney adaptor for maximum reproducibility. The same syringe was used for sample and standard to avoid systematic volume errors.

The uncertainties are the standard deviations from the mean for eight or nine hydrogenations, alternating sample with standard. They express approximately 95% confidence limits. Thermographs were varied, some being normal (palladium catalyst, Figure 2a), others showing a slow reaction following the initial temperature rise (platinum catalyst, Figure 2b).

Computational procedures: All MM3 calculations were performed with the program Alchemy 2000, 2.0.[30] B3LYP/6-31G* calculations were performed with the GAUSSIAN 98 suite of programs.[32] Becke's nonlocal three-parameter exchange functional (B3)[48] as implemented in GAUSSIAN 98 in conjunction with the nonlocal Lee-Yang-Parr correlation functional (LYP)[49] and Pople's 6-31G* split valence basis set was used. High-level density functional (DFT) calculations were performed using the DFT program ADF (version 2.3.6).[31] The MOs were expanded in a large uncontracted set of Slater type orbitals (STOs). The basis is of triple-ξ quality (three STOs per nl shell), augmented with one polarization function on each atom: 2p on H; 3d on C. The cores were treated by the frozen-core approximation (C, 1s). Optimisations were carried out without imposing geometric constraints. The numerical integration was performed by the procedure developed by te Velde et. al.[31b] Energies were evaluated using the local spin density approximation (LSDA), characterised by the electron gas exchange (Slaters potential, Xα, with $\alpha = 2/3$)[50] with nonlocal corrections due to Becke.[51] Correlation is treated by the Vosko-Wilk-Nusair (VWN) parametrisation[52] with nonlocal corrections proposed by Perdew.[53]

Crystal structure determination of 8c′: $C_{12}H_{17}BrCl_2$, $M_r = 312.08$, colourless, plate-shaped crystal ($0.2 \times 0.5 \times 0.7$ mm), triclinic, space group $P\bar{1}$ (no. 2) with $a = 7.6832(8)$, $b = 8.0031(8)$, $c = 10.0508(7)$ Å, $\alpha = 97.476(7)$, $\beta = 91.216(7)$, $\gamma = 90.226(8)^\circ$, $V = 612.61(10)$ Å^3, $Z = 2$, $D_x = 1.692$ g cm^{-3}, $F(000) = 316$, $\mu(Mo_{K\alpha}) = 3.76$ mm^{-1}. 5487 Reflections measured, 2799 independent, $R_{int} = 0.111$, ($2.05^\circ < \Theta$ 27.5°, ω scan, $T = 150$ K, $Mo_{K\alpha}$ radiation, graphite monochromator, $\lambda = 0.71073$ Å) on an Enraf–Nonius CAD4 Turbo diffractometer onrotating anode. Data were corrected for Lp effects, linear instability of the reference reflections, and for absorption (based on observed ψ-scans[54]). The structure was solved by automated direct methods (SHELXS86[55]). Refinement on F^2 carried out by full-matrix least-squares techniques (SHELXL-97[56]); no observance criterion was applied during refinement. The measured crystal was found to contain a small amount of **8c**, resulting in a disorder of the halogen atoms on C(12). The site occupation factor of the major component refined to 0.916(2). Mild bond length restraints were applied to enforce equal bond lengths and angles in both configurations of the CClBr moiety. Hydrogen atoms were included in the refinement on calculated positions riding on their carrier atoms. All ordered non-hydrogen atoms and the major component of the disordered atoms were refined with anisotropic displacement parameters; hydrogen atoms were refined with a fixed isotropic atomic displacement parameter related to the value of the equivalent isotropic displacement parameter of their carrier atoms. Refinement of 143 parameters converged at final w$R2$ value of 0.1042, $w = 1/[\sigma^2(F^2) + (0.0150P)^2 + 0.97P]$, where $P = (\mathrm{Max}(F_o^2, 0) + 2F_o^2)/3$, $R1 = 0.0405$, (for 2509 reflections with $I > 2\sigma(I)$), $S = 1.068$. A final difference Fourier showed no residual π-density outside -0.95 and 0.63 eÅ^{-3} (near Br).

Crystallographic data (excluding structure factors) for the structure reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-140361. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB21EZ, UK (fax: (+44) 1223-336-033; e-mail: deposit@ccdc.cam.ac.uk).

Acknowledgement

This investigation was supported in part (M.J.v.E., G.W.W., A.L.S.) by the Council of Chemical Sciences (GCW) with financial aid from the Netherlands Organization for Scientific Research (NWO). We thank Dr. F.J.J. de Kanter for the interpretation of the NMR spectra.

[1] a) D. J. Cram, H. J. Steinberg, *J. Am. Chem. Soc.* **1951**, *73*, 5691; b) F. Bickelhaupt, W. H. de Wolf, *Adv. Strain Org. Chem.* **1993**, *3*, 185; c) F. Bickelhaupt, W. H. de Wolf, *J. Phys. Org. Chem.* **1998**, *11*, 362–376; d) F. Vögtle, *Cyclophane Chemistry*, Wiley, Chichester, **1993**.

[2] a) K. J. Shea, L. D. Burke, R. J. Doedens, *J. Am. Chem. Soc.* **1985**, *107*, 5305; b) L. W. Jenneskens, J. C. Klamer, H. J. R. de Boer, W. H. de Wolf, F. Bickelhaupt, C. H. Stam, *Angew. Chem.* **1985**, *96*, 236; *Angew. Chem. Int. Ed. Engl.* **1985**, *23*, 238; c) P. C. M. van Zijl, L. W. Jenneskens, E. W. Bastiaan, C. MacLean, W. H. de Wolf, F. Bickelhaupt, *J. Am. Chem. Soc.* **1986**, *108*, 1415.

[3] G. B. M. Kostermans, P. van Dansik, W. H. de Wolf, F. Bickelhaupt, *J. Am. Chem. Soc.* **1987**, *109*, 7887.

[4] J. W. van Straten, W. H. de Wolf, F. Bickelhaupt, *Tetrahedron Lett.* **1977**, 4667.

[5] L. W. Jenneskens, F. J. J. de Kanter, P. A. Kraakman, L. A. M. Turkenburg, W. E. Koolhaas, W. H. de Wolf, F. Bickelhaupt, Y. Tobe, K. Kakiuchi, Y. Odaira, *J. Am. Chem. Soc.* **1985**, *107*, 3716.

[6] C. F. Shieh, D. McNally, R. H. Boyd, *Tetrahedron* **1969**, *25*, 3653.

[7] H. Dreeskamp, S. M. Sarge, W. Tochtermann, *Tetrahedron* **1995**, *51*, 3137.

[8] L. W. Jenneskens, F. J. J. de Kanter, W. H. de Wolf, F. Bickelhaupt, *J. Comput. Chem.* **1987**, *8*, 1154.

[9] L. W. Jenneskens, J. N. Louwen, F. Bickelhaupt, *J. Chem. Soc. Perkin Trans. 2* **1989**, *135*, 1893.

[10] M. J. van Eis, W. H. de Wolf, F. Bickelhaupt, R. Boese, *J. Chem. Soc. Perkin 2* **2000**, in press.

[11] S. W. Benson, *Thermochemical Kinetics*, 2nd ed., Wiley, New York, **1976**.

[12] D. W. Rogers, H. von Voithenberg, N. L. Allinger, *J. Org. Chem.* **1978**, *43*, 360.

[13] J. Bredt, H. Thouet, J. Schmitz, *Justus Liebigs Ann. Chem.* **1924**, *437*, 1.

[14] D. R. Stull, E. F. Westrum, Jr., G. C. Sinke, *The Chemical Thermodynamics of Organic Compounds*, Wiley, New York, **1969**.

[15] G. B. Kistiakowsky, J. R. Ruhoff, H. A. Smith, W. E. Vaughan, *J. Am. Chem. Soc.* **1936**, *58*, 146.

[16] See also: V. I. Minkin, M. N. Glukhovtsev, B. YA. Simkin, *Aromaticity and Antiaromaticity*, Wiley, New York, **1994**, pp. 75–77.

[17] W. Hemminger, G. Hohne, *Calorimetry, Fundamentals and Practice*, Verlag Chemie, Weinheim, **1984**, p. 83.

[18] L. A. M. Turkenburg, P. M. L. Blok, W. H. de Wolf, F. Bickelhaupt, *Tetrahedron Lett.* **1981**, *22*, 3317.

[19] G. W. Wijsman, W. H. de Wolf, F. Bickelhaupt, *J. Am. Chem. Soc.* **1992**, *114*, 9191.

[20] a) C. G. Cardenas, A. N. Khafaji, C. L. Osborn, P. D. Gardner, *Chem. Ind.* **1965**, 345; b) C. L. Osborn, T. C. Schields, B. A. Shoulders, C. G. Cardenas, P. D. Gardner, *Chem. Ind.* **1965**, 766; c) J. Hatem, B. Waegell, *Tetrahedron* **1990**, *46*, 2789; d) G. W. Wijsman, W. H. de Wolf, F. Bickelhaupt, *Recl. Trav. Chim. Pays-Bas* **1994**, *113*, 53.

[21] L. A. M. Turkenburg, J. W. van Straten, W. H. de Wolf, F. Bickelhaupt, *J. Am. Chem. Soc.* **1980**, *102*, 3256.

[22] W. Fang, D. W. Rogers, *J. Org. Chem.* **1992**, *57*, 2294.

[23] a) W. R. Roth, H.-W. Lennartz, *Chem. Ber.* **1980**, *113*, 1806; b) D. W. Rogers, *J. Phys. Chem.* **1979**, *83*, 2430.

[24] W. Grimme, A. Bertsch, H. Flock, T. Noack, S. Krauthäuser, *Synlett*, **1998**, 1175.

[25] T. J. Nieuwstad, F. Klapwijk, H. van Bekkum, *J. Catalysis* **1973**, *29*, 404, and references therein; M. B. Smith, *Organic Synthesis*, McGraw-Hill, New York, **1994**, 423–450.

[26] a) S. T. Lin, R. L. Wharry, R. L. Yates, N. Garti, J. Pranata, S. Siegel, P. Skrabal, *J. Org. Chem.* **1994**, *59*, 7056; b) F. M. Yang, S. T. Lin, *J. Org. Chem.* **1997**, *62*, 2727.

[27] a) Z. H. Li, M. Jones, Jr. *Tetrahedron Lett.* **1987**, *28*, 753; b) For the similar hydrogenation of [6]paracyclophane, see: J. Liebe, C. Wolff, C. Krieger, J. Weiss, W. Tochtermann, *Chem. Ber.* **1985**, *118*, 4144.

[28] a) W. F. Maier, P. v. R. Schleyer, *J. Am. Chem. Soc.* **1981**, *103*, 1891; b) A. B. McEwen, P. v. R. Schleyer, *J. Am. Chem. Soc.* **1986**, *108*, 3951.

[29] For examples of hyperstable olefins, see: a) H. Kukuk, E. Proksch, A. de Meijere, *Angew. Chem.* **1982**, *94*, 304; *Angew. Chem. Int. Ed. Engl.* **1982**, *21*, 306; b) Y. Tobe, T. Kishimura, K. Kakiuchi, Y. Odaira, *J. Org. Chem.* **1983**, *48*, 551; c) Y. Tobe, Y. Ueda, M. Matsumoto, Y. Sakai, Y. Odaira, *Tetrahedron Lett.* **1982**, *23*, 537; d) J. E. McMurry, C. N. Hodge, *J. Am. Chem. Soc.* **1984**, *106*, 6450.

[30] Alchemy 2000, 2.0 Licence No 01–0009081, Copyright 1997 TRIPOS, INC.

[31] ADF 2. 3.6, Theoretical Chemistry, Vrije Universiteit, Amsterdam: a) E. J. Baerends, D. E. Ellis, P. Ros, *Chem. Phys.* **1973**, *2*, 41; b) G. te Velde, E. J. Baerends, *J. Comp. Phys.* **1992**, *99*, 84; c) C. Fonseca Guerra, O. Visser, J. G. Snijders, G. te Velde, E. J. Baerends in *Methods and Techniques for Computational Chemistry* (Eds.: E. Clementi, G. Corongiu), STEF, Cagliari, Italy, **1995**, pp. 305–395.

[32] All B3LYP/6–31G* calculations were performed with the Gaussian 98 suite of programs: M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, V. G. Zakrzewski, J. A. Montgomery, Jr., R. E. Stratmann, J. C. Burant, S. Dapprich, J. M. Millam, A. D. Daniels, K. N. Kudin, M. C. Strain, O. Farkas, J. Tomasi, V. Barone, M. Cossi, R. Cammi, B. Mennucci, C. Pomelli, C. Adamo, S. Clifford, J. Ochterski, G. A. Petersson, P. Y. Ayala, Q. Cui, K. Morokuma, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. Cioslowski, J. V. Ortiz, B. B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. Gomperts, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, C. Gonzalez, M. Challacombe, P. M. W. Gill, B. Johnson, W. Chen, M. W. Wong, J. L. Andres, C. Gonzalez, M. Head-Gordon, E. S. Replogle, J. A. Pople, Gaussian, Inc., Pittsburgh PA, **1998**.

[33] O. Ermer, *Angew. Chem.* **1974**, *86*, 672; *Angew. Chem. Int. Ed. Engl.* **1974**, *13*, 604.

[34] O. Ermer, *Aspekte von Kraftfeldrechnungen*, Bauer, München, **1981**.

[35] For a comprehensive review of the strain in olefines and a description of the different modes of distortion (pyramidalisation versus twisting), see: a) P. Warner, *Chem. Rev.* **1989**, *89*, 1067; b) W. T. Borden, *Chem. Rev.* **1989**, *89*, 1095.

[36] For a discussion of the degree of pyramidalisation in olefines, see: R. C. Haddon, *J. Am. Chem. Soc.* **1990**, *112*, 3385.

[37] For calculational studies on bridgehead olefins in addition to those in Ref. [28] see: a) S. Peacock, P. M. Warner, *J. Comp. Chem.* **1982**, *3*, 417; P. M. Warner, S. Peacock, *Tetrahedron Lett.* **1983**, *24*, 4169.

[38] a) S. Kaarsemaker, J. Coops, *Recl. Trav. Chim.* **1952**, *71*, 261; b) J. Coops, H. van Kamp, W. A. Lambgrets, B. J. Visser, H. Dekker, *Recl. Trav. Chim.* **1960**, *79*, 1226.

[39] A value of 92 kJ mol^{-1} has been reported employing the MM1 method, Ref. [28a].

[40] This value corresponds well with the MM2 derived value of 4.6 kJ mol^{-1}, C. S. Swindell, T. F. Isaacs, K. J. Kanes, *Tetrahedron Lett.* **1985**, *26*, 289.

[41] L. A. Curtiss, K. Rhagavachari, P. C. Redfern, J. A. Pople, *Chem. Phys. Lett.* **1997**, *270*, 419.

[42] Recently, it was pointed out that a substantial discrepancy exists between the experimental value and the B3LYP result for the heat of formation of norbornadiene, norbornene and norbornane; note, however, that these errors are largely compensated in the calculated heats of hydrogenation: D. W. Rogers, F. J. McLafferty, *J. Phys. Chem. A* **1999**, *103*, 8733.

[43] L. W. Jenneskens, L. A. M. Turkenburg, W. H. de Wolf, F. Bickelhaupt, *Recl. Trav. Chim. Pays-Pas* **1985**, *104*, 184.

[44] L. W. Jenneskens, F. J. J. de Kanter, W. H. de Wolf, F. Bickelhaupt, *Magn. Reson. Chem.* **1986**, *24*, 308.

[45] S. Hirano, H. Hara, T. Hiyama, S. Fujita, H. Nozaki, *Tetrahedron* **1975**, *31*, 2219.

[46] L. W. Jenneskens, H. J. R. de Boer, W. H. de Wolf, F. Bickelhaupt, *J. Am. Chem. Soc.* **1990**, *112*, 8941.

[47] Sartorius M3P, Sartorius GmbH, Göttingen, Germany.

[48] A. D. Becke, *J. Chem. Phys.* **1993**, *98*, 1372, 5648.

[49] C. Lee, W. Yang, G. Parr, *Phys. Rev. B* **1988**, *37*, 785.

[50] J. C. Slater, in *Quantum Theory of Molecules and Solids*, *Vol. 4*, McGraw-Hill, New York, **1974**.

[51] a) A. D. Becke, *Chem. Phys.* **1986**, *84*, 4524; b) A. D. Becke, *Phys. Rev. A* **1988**, *38*, 3098.

[52] S. H. Vosko, L. Wilk, M. Nusair, *Can. J. Phys.* **1980**, *58*, 1200.

[53] J. P. Perdew, *Phys. Rev. B.* **1986**, *33*, 8822.

[54] A. L. Spek, *Acta Crystallogr.* **1990**, *A46*, C-34.

[55] G. M. Sheldrick, SHELXS86 Program for crystal structure determination. University of Göttingen, Germany, **1986**.

[56] G. M. Sheldrick, SHELXl-97–2 Program for crystal structure refinement. University of Göttingen, Germany, **1997**.

Received: September 23, 1999 [F2052]

  0947-6539/00/0609-1546 $ 17.50+.50/0