  Bull. Chem. Soc. Jpn., 61, 155—163 (1988)

Invited Paper

Syntheses and Dynamic Behavior of Chiral Heptalenes

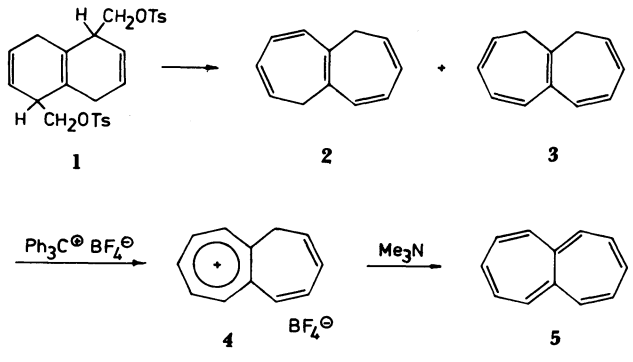
Klaus HAFNER,* Günter L. KNAUP, and Hans Jörg LINDNER
Institut für Organische Chemie der Technischen Hochschule Darmstadt,
Petersenstrasse 22, D-6100 Darmstadt, F.R.G.
(Received August 31, 1987)

Cycloaddition reactions of azulenes with dimethyl acetylenedicarboxylate afford an excellent access to a large variety of substituted dimethyl 1,2-heptalenedicarboxylates. These can be converted into various methylheptalenes, which proved to be remarkably stable. This allowed for the first time a separation of the bond shift isomers as well as an optical resolution of derivatives of this axial chiral 12π-electron system. Kinetic studies of bond shifting and ring inversion provide information on the transition states of these dynamic processes.

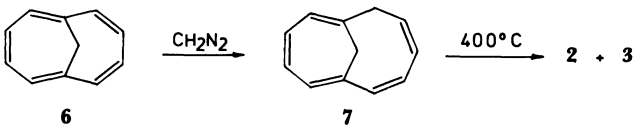
Since Hückel introduced his famous rule[1] that a monocyclic planar π-electron system should be aromatic if it contains [4*n*+2] π-electrons, a large number of neutral and ionic ring systems[2] had been prepared in order to test the validity of this aromaticity concept. The investigations verified a clear distinction in the chemical and physical properties between the [4*n*+2] and 4*n* π-electron systems and completely justified Hückels rule. For instance, the two species differ characteristically in the ^{1}H NMR spectra. While the outer protons of the [4*n*+2] π-systems show a low field shift caused by a diamagnetic ring current,[3] those of the 4*n* π-systems show a high field shift, which could be attributed to a paramagnetic contribution arising from the mixing of excited states with the ground state.[4] Whereas the HMO-theory originally only predicted that [4*n*+2] π-systems should be more stable than 4*n* π-systems, later theories suggested that the 4*n* π-systems should be destabilized by delocalization and should be in fact antiaromatic.[5] This is valid not only for annulenes, but also for bicyclic systems derived from annulenes bridged by an essential single bond. Indeed, the smallest members of the mono- and bicyclic annulenes, cyclobutadiene[2] and pentalene,[6] are so reactive, that they can not be isolated. Another significant difference is the fact that mono- and bicyclic systems with 4*n* π-perimeters possess localized double bonds in the ground states. Therefore, the structures with delocalized bonds are only transition states on the potential surfaces which connect the localized bond systems with one another. This could be established for tetra-*t*-butylcyclobutadiene,[7] 1,3,5-tri-*t*-butylpentalene,[8] cyclooctatetraene,[9] and heptalene.[10] In contrast to cyclobutadiene and pentalene, the higher homologues, cyclooctatetraene and heptalene, are characterized by nonplanar structures. Thus, from each of these systems exist four isodynamic structures, which are, via bond shifting and ring inversion, in a dynamic equilibrium with one another. A study of both dynamic processes should provide information on their transition states and, therefore, also on the antiaromaticity of the delocalized systems. Assuming planar delocalized transition states for the bond shift and planar localized transition states for the ring inversion, the difference between the activation enthalpies of both processes should be equal to the delocalization energies for the planar ring systems. For cyclooctatetraene, Oth[9] determined by NMR measurements of the ethoxy derivative a difference of 3.5 kcal mol^{-1}, which he attributed to the energy required for the delocalization of the planar 8π-perimeter. A similar value was calculated by Paquette et al.[11] from the differences of the activation enthalpies of methyl-substituted cyclooctatetraenes taking into account different steric strains in the assumed planar localized and delocalized transition states. In the case of the 1,2,3-tri- and 1,2,3,4-tetramethylcyclooctatetraenes, even a separation of the bond shift isomers and an enrichment of the enantiomers was possible.[12]

Syntheses and Physical Properties of Heptalenes

Dauben and Bertelli[13] demonstrated in 1961 that the dihydroheptalenes **2** and **3** can be transformed into heptalene **5** by hydride abstraction and subsequent

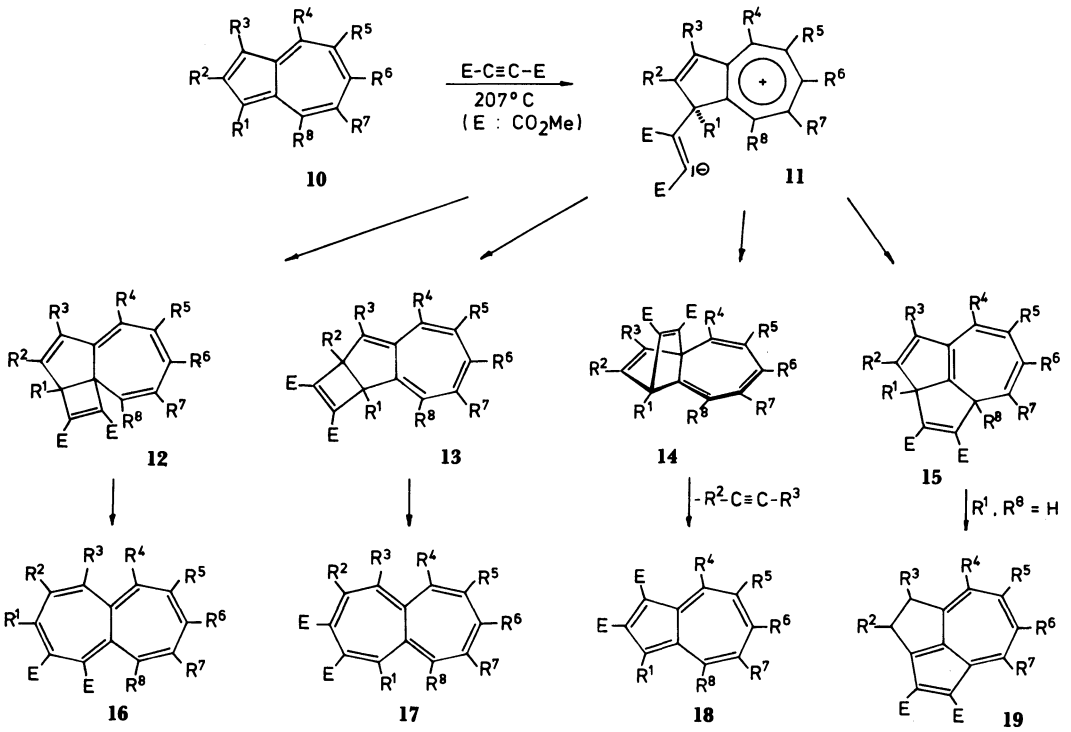


Scheme 1.



Scheme 2.

deprotonation of the resulting heptalenium salt **4** (Scheme 1). Since then, additional syntheses of the bicyclic 12π-system **5** were published[14] using this method. While Dauben and Bertelli[15] prepared a mixture of **2** and **3** by solvolytic rearrangement of the isotetralin **1**, Vogel et al.[10] obtained a similar mixture by pyrolysis of **7**, which was prepared by ring expansion of 1,6-methano[10]annulene **6** (Scheme 2).

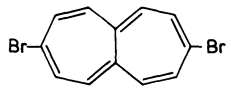


Scheme 3.

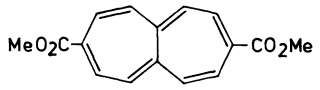
10—19	R¹	R²	R³	R⁴	R⁵	R⁶	R⁷	R⁸	Yield/%			
									16	**17**	**18**	**19**
a	H	H	H	H	H	H	H	H	25	—	2	1
b	H	H	Me	H	H	H	H	H	23	17	3[a]	1
c	H	H	*t*-Bu	H	H	H	H	H	2	1	21	—
d	H	H	H	H	H	H	H	Me	35[b]	—	2[b]	—[b]
e	Me	H	Me	H	H	H	H	H	—	—	40	—
f	H	H	Me	Me	H	H	H	H	—	—	42	—
g	H	H	Me	H	H	H	H	Me	53	—	10	—
h	H	H	H	Me	H	H	H	Me	44	—	3	—
i	H	H	H	Me	H	Me	H	Me	56	—	8	—
j	H	H	Me	Me	H	H	H	Me	32	—	55	—
k	H	H	Me	Me	H	Me	H	Me	40	2	21	—
l	H	Me	H	Me	H	Me	H	Me	56	—	3	—
m	H	*i*-Pr	H	Me	H	Me	H	Me	56	—	6	—
n	H	*t*-Bu	H	Me	H	Me	H	Me	55	—	—	—
o	H	H	*i*-Pr	Me	H	Me	H	Me	7	—	53	—
p[21]	H	H	Me	H	*i*-Pr	H	H	Me	63	—	6	—
q	H	H	$-(CH_2)_2-$		H	H	H	H	—	—	—	—[c]
r	H	H	$-(CH_2)_3-$		H	H	H	H	8	5	—	—
s	H	H	$-(CH_2)_4-$		H	H	H	H	35	23	—	1
t	H	H	$-(CH_2)_4-$		H	Me	H	Me	51	1	—	—
u	H	H	H	Me	H	OMe	H	Me	43	—	10	—
v	H	H	H	H	H	CO_2Et	H	H	10	—	—	—

a) and 1% dimethyl 3-methylazulene-1,2-dicarboxylate b) and 3% dimethyl 6-methylheptalene-1,2-dicarboxylate, 1% dimethyl 4-methylazulene-2,3-dicarboxylate, 4% dimethyl 5-methyl-3,4-dihydrocyclopent[*cd*]azulene-1,2-dicarboxylate c) and 7% dimethyl 3,4-dihydrocyclopent[*cd*]azulene-1,2-dicarboxylate.

In 1979, both Vogel et al.[16] and Paquette et al.[17] developed heptalene syntheses based on dibromocarbene additions to isotetralin. Similarly 3,8-dibromoheptalene **8**[18] and dimethyl heptalene-3,8-dicarboxylate **9**[19] can be prepared. In contrast to these multistep



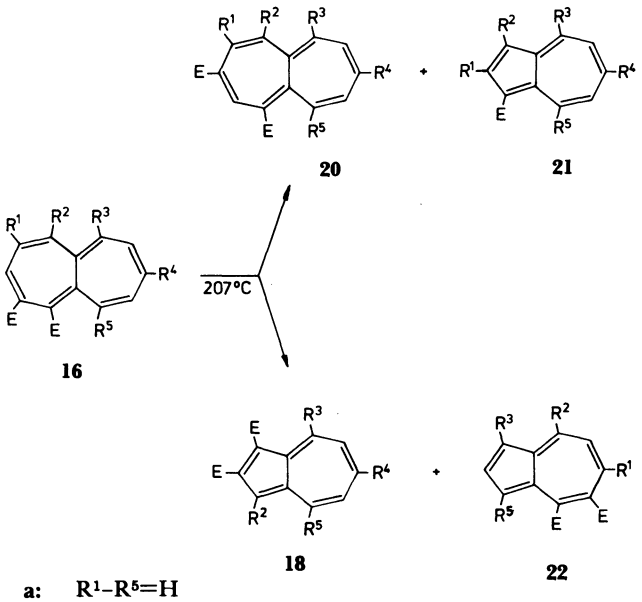
8



9

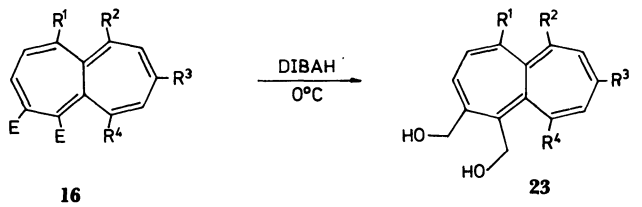
syntheses, we developed an extremely simple, onepot synthesis, which allows the preparation of numerous substituted heptalene-1,2-dicarboxylates.[20] Cycloaddition of dimethyl acetylenedicarboxylate to azulenes **10** in boiling tetralin affords the dimethyl heptalene-1,2-dicarboxylates **16** in yields up to 64%. Side products of these reactions are the dimethyl heptalene-2,3-dicarboxylates **17**, the dimethyl azulene-1,2-dicarboxylates **18** and the dimethyl 3,4-dihydrocyclopent[*cd*]azulene-1,2-dicarboxylates **19** in varying yields (Scheme 3). The formation of all these compounds can be rationalized by invoking **11** as an intermediate formed by an electrophilic attack of the electron-deficient alkyne to the azulene. Ring closure of **11** should lead to the adducts **12**—**15**, which then isomerize to the heptalenes **16**, **17**, and the azulene derivatives **18**, **19**, respectively. The drastic reaction conditions required for the cycloaddition did not allow the detection of the proposed intermediates. However, if the reaction is carried out at 7 kbar and 50 °C, the [4+2] adduct **14** becomes the main product.[22]

In contrast to the parent compound **5**, the 3,8-disubstituted derivatives **8**, **9**, and the heptalenedicarboxylates **16**, **17** are remarkably stable. However, in boiling tetralin **16** undergoes a slow irreversible rearrangement to heptalene-1,3-dicarboxylates **20** and a ring contraction to the azulene derivatives **18**, **21**, and **22**. The rate of this reaction and the ratio of the products depend strongly on the substituents.[23] While the thermolysis of the dimethyl heptalene-1,2-dicarboxylate **16a** yields predominantely the azulenes **18a**, **21a**, and **22a**, and only traces of the heptalene-1,3-dicarboxylate **20a**, compounds of this type become the main products by the thermolyses of methyl-substituted heptalenedicarboxylates (Scheme 4). As we could show, the stability of heptalenes not only increases by electron-withdrawing substituents in the 1- or 3-position (the positions with high electron densities) but also by alkyl substituents in the peri-positions. Therefore, reduction of the dimethyl heptalenedicarboxylates **16** with diisobutylaluminum hydride (DIBAH) afford the 1,2-bis(hydroxymethyl)-heptalenes **23** as thermally and air-stable yellow crystals[24,25] (Scheme 5). Due to the chiral heptalene system, the diastereotopic hydroxymethyl groups appear in the ^{1}H NMR spectra as AB spin systems with vicinal coupling constants around 15 Hz. The tetramethyl derivative **23k** can be converted into the dichloride **24b**, which can be reduced with lithium triethylborohydride to the hexamethylheptalene **26**.[24] In contrast to **24b**, the trimethyl derivative **24a** is unstable at room temperature but rather eliminates HCl spontaneously to the dimethylidene compound **25**[25] (Scheme 6). Similarly to the HCl elimination of **24a**, the diols **23** can be dehydrated by treatment with catalytic amounts of *p*-toluenesulfonic acid in boiling benzene.[25] These reactions lead (probably via an enolic structure similar to **25** to the heptalene-2-carbaldehydes **27**. Decarbonylation of **27** with chlorotris(triphenylphosphin)rhodium(I) yields the methylheptalenes **28** as thermally and airstable compounds[25] (Scheme 7). In addition to **28a**—**d** we also synthesized 1,6-dimethylheptalene **31** by an



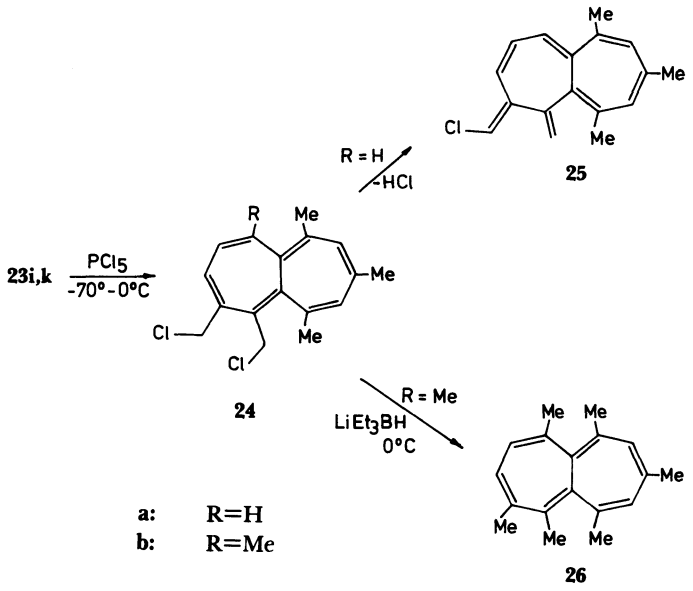
a: R^1–R^5=H
d: R^1–R^4=H, R^5=Me
i: R^1,R^2=H, R^3–R^5=Me
k: R^1=H, R^2–R^5=Me
l: R^2=H, R^1,R^3–R^5=Me

Scheme 4.

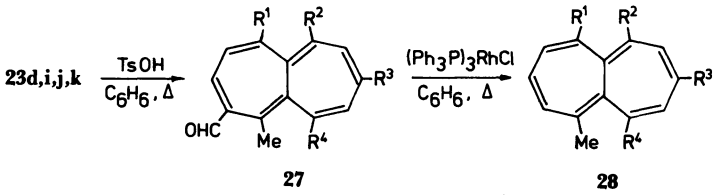


b: R^1=Me, R^2–R^4=H
d: R^1–R^3=H, R^4=Me
i: R^1=H, R^2–R^4=Me
j: R^3=H, R^1,R^2,R^4=Me
k: R^1–R^4=Me

Scheme 5.

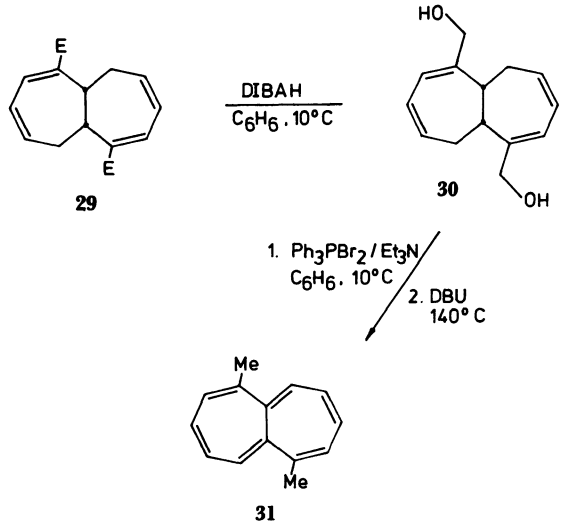


Scheme 6.



a: R^1–R^3=H, R^4=Me
b: R^1=H, R^2–R^4=Me
c: R^1,R^2,R^4=Me, R^3=H
d: R^1–R^4=Me

Scheme 7.



Scheme 8.

entirely different pathway after the dimethyl *cis*-1,5a,6,10a-tetrahydroheptalenedicarboxylate **29** became readily available by a new rearrangement reaction.[26]

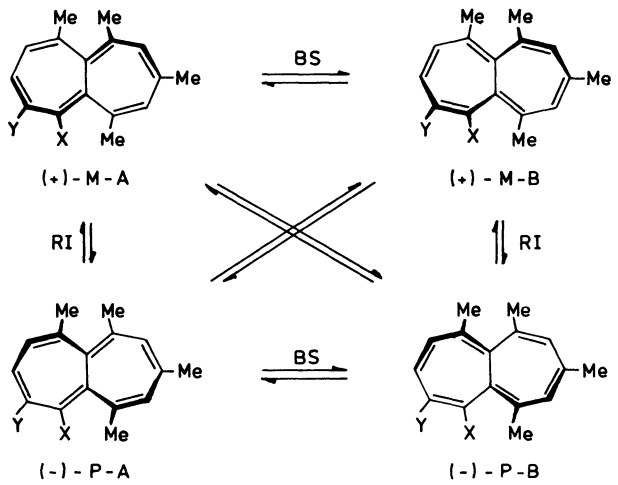
Reduction of **29** with DIBAH and subsequent twofold dehydration of the resulting alcohol **30** affords the heptalene **31** as a yellow oil[25] (Scheme 8). In contrast to the extremely air-sensitive and thermally unstable parent compound **5**, the described methylheptalenes — even the dimethyl derivatives **28a** and **31** — are surprisingly stable. This could not only be a result of a kinetic stabilization due to a steric shielding of the heptalene system, but rather to an enhancement of twisting of the nonplanar 12π-perimeter caused mainly by the steric interaction of the substituents in the peri-positions. This reduces the cyclic conjugation and increases the HOMO–LUMO gap and, therefore, reduces the reactivity of the $4n$ π-system.

Resolution and Chiroptical Properties of Chiral Heptalenes

Heptalenes, as most other $4n$ π-systems, show in the ground state π-bond fixation. Therefore, from unsymmetrically substituted heptalenes exist two nonequivalent bond shift isomers. The ratio of these isomers depends on the substituents. For the un- and

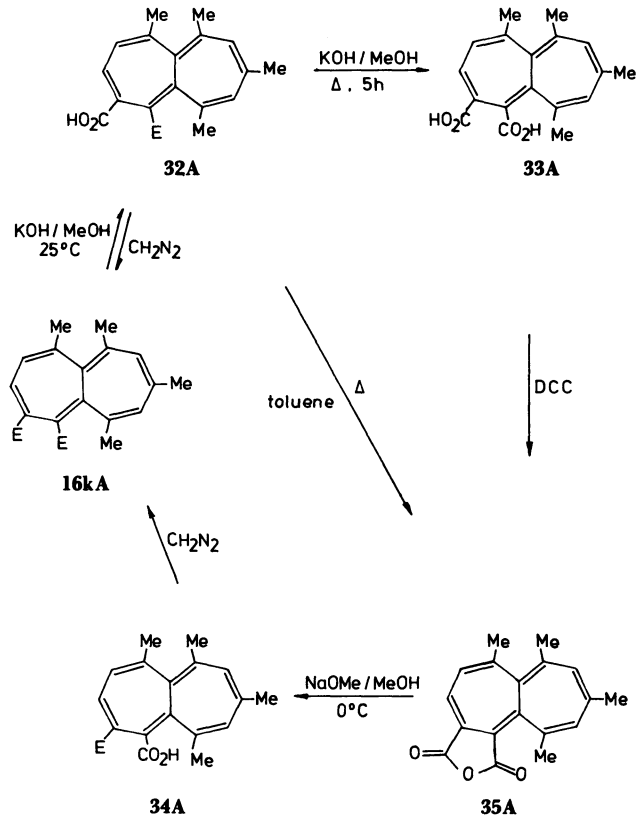
monosubstituted dimethyl heptalene-1,2-dicarboxylates **16a—d** and the bridged derivatives **16r—t** only the bond shift isomers with a single bond between the ester groups can be observed in the ^{1}H NMR spectra. However, for **16g—o**, which have two or three alkyl substituents in the peri-positions, 10—30% of the other bond shift isomers can be detected. The preference of the isomers with a single bond between the ester groups can be explained by the tendency of the carboxylate groups to assume a coplanar arrangement to the adjacent double bonds of the ring system, which is sterically hindered in the other isomers. In contrast to some heptalene-1,2-dicarboxylates **16**, both bond shift isomers of the diols **23**, the 2-carbaldehydes **27** as well as the methylheptalenes **26** and **28** can be detected in varying ratios in the ^{1}H NMR spectra. Although a unique trend has not been found so far, an effect is evident. The isomer with the lowest number of substituents in the peri-positions having a double bond to the bridge atoms C-5a and C-10a is thermodynamically more stable than the other. This might be due to a smaller steric interaction across the peri-positions in this bond shift isomer.

X-Ray analyses[27] of the heptalene dicarboxylates **9** and **16a** confirmed a C_2-geometry for the heptalene system with the two annelated seven-membered rings in boat conformations. Therefore, for heptalenes should, according to Oth et al.,[28] exist four isodynamic axial chiral structures which are, via bond shift (BS) and ring inversion (RI), in a dynamic equillibrium with one another (Scheme 9). So far, π-bond shift has been investigated in heptalene itself (E_a=3.5 kcal mol^{-1}),[10] heptalene-1,6-dicarbaldehyde (ΔG^*=9.9 kcal mol^{-1}),[16] dimethyl heptalene-1,6-dicarboxylate (ΔG^*=14 kcal mol^{-1}),[16] and dimethyl 6,8,10-trimethylheptalene-1,2-dicarboxylate **16i** (ΔG^*=21.7 and 21.0 kcal mol^{-1}, respectively).[29] For the latter, the bond shift isomers can even be separated by low temperature chromatography. As these results indicate, the energy barrier for the bond shift increases with the number of substituents in the peri-positions of the heptalenes. In fact, for the dimethyl 5,6,8,10-tetramethylheptalene-1,2-dicarboxylate **16k** we succeeded for the first time in isolating in pure form all four isomers (+)-M-**A**, (+)-M-**B**, (−)-P-**A**, and (−)-P-**B** of a $4n$ π-system.[30,31] The bond shift isomers rac-**A** and rac-**B** of **16k** can be separated by simple chromatography on alumina at room temperature. Both bond shift isomers differ characteristically in their NMR and UV spectra. While the protons H-3 and H-4 of **16kA** show a coupling constant of 6.9 Hz, those of **16kb** appear as an AB spin-system with a coupling constant of 11.8 Hz. These values are characteristic for coupling constants via single and double bonds in substituted heptalenes and allow a simple assignment of the positions of the double bonds. The structures of the bond shift isomers A and B of **16k** were also established by X-ray analyses.[30] Although the optical resolution can be carried out by HPLC on triacetylcellulose,[32] for a preparative scale separation we prefered the classic method of fractional crystallization of diastereomeric salts. For that the diesters **16kA**



	16k	23k	24b	26	32
X	CO_2Me	CH_2OH	CH_2Cl	Me	CO_2Me
Y	CO_2Me	CH_2OH	CH_2Cl	Me	CO_2H

Scheme 9.



Scheme 10.

and **16kB** were converted into the free acids with potassium hydroxide in methanol. If the reactions are carried out at room temperature, selectively **32A** and **32B** with the carboxylic acid group in 2-position are obtained without bond shift isomerization. On the other hand, the preparation of the dicarboxylic acid **33A** requires considerably higher temperatures. Both the mono-**32A** and the dicarboxylic acid **33A** can be converted into the anhydride **35A**, which selectively affords the 1-carboxylic acid **34A** by treating with sodium methoxide (Scheme 10). The selectivity of the saponification of **16k** and the esterification of **35A** might be due to a steric shielding of the carboxylate group in the 1-positions caused by the methyl groups in the 8-position. In fact, heptalene-1,2-dicarboxylates without substituents in the 8-position, i.e. **16a—d**, yield under the same reaction conditions mixtures of the corresponding 1- and 2-carboxylic acids. By our experience, the best optically active amines suitable for the resolution of the 2-carboxylic acids **32** are cinchonine and (+)-1-phenylethylamine for **32A** and (+)- and (−)-ephedrine for **32B**. With these amines, the heptalenes (+)-M-**32A**, (+)-M-**32B**, (−)-P-**32A**, and (−)-P-**32B** were obtained with an enantiomeric purity of greater than 98%, as determined by NMR spectroscopy of the diastereomeric ephedrine salts. The optically active heptalenecarboxylic acids **32** and the diesters **16k**, prepared from **32** with diazomethane without racemization, have very high specific optical rotations (Table 1), typical for systems with helical chiral chromophores. The absolute configuration of the chiral heptalenes was achieved by X-ray analysis of the (+)-ephedrine salt of (+)-M-**32A**. Since both bond shift isomers of (+)-M-**32** show very similar CD-spectra (characterized by two positive Cotton effects at 358, 321 nm, and 380, 312 nm, respectively, and two negative Cotton effects at 280, 252 nm, and 278, 224 nm, respectively) (Fig. 1), the two bond shift isomers must have the same absolute configuration. Although the bond shift isomers of the dimethyl 6,8,10-trimethylheptalene-1,2-dicarboxylate **16i** undergo at room temperature in solution a fast interconversion, they are stable in the crystalline form. NMR spectra taken of solutions of these crystals show each to be isomerically pure. While crystallization from hexane/ether of **16i** and the 4-isopropyl- and 4-*t*-butyl derivatives **16m** and **16n** affords selectively the thermodynamically more stable isomers (single bond between the ester groups), the tetramethyl derivative **16l** crystallizes to give only the other isomer. So far, all attempts for an optical resolution, or at least an enrichment of one of the enantiomeres, of **16i** by fractional crystallization of salts of the carboxylic acid **36** with optically active amines have failed. This is probably due to the existence of both bond shift isomers of **16i** in solution. Nevertheless, a resolution could be achieved with the (−)-menthyl ester **38**, prepared from the anhydride **37** with (−)-menthol and subsequent esterification with diazomethane (Scheme 11). Crystallization at room temperature leads selectively to the (−)-menthyl-(−)-P-heptalene diastereomer (−)-**38A**. However, the ^{1}H NMR spectra at room temperature clearly show that the four diastereomers (−)-**38A**, (+)-**38A**, (−)-**38B**, and (+)-**38B** exist in the equilibrium in a ratio of 5.5:3.3:1.2:1. Reduction of the enantiomerically pure diesters (−)-P-**16kA** and (−)-P-**16kB** with diisobutylaluminium hydride affords the alcohols (−)-P-**23kA** and (−)-P-**23kB** with enantiomeric purities of greater than 98%, as shown by ^{1}H NMR spectra using the chiral shift reagent Eu(hfc)$_3$. Since these optically active alcohols, which have no electron-withdrawing substituents, show CD-spectra very similar to the heptalene-1,2-

Table 1. Specific Optical Rotations of the Heptalenes (+)-M-**16k**, (−)-P-**23k**, (+)-M-**32**, and (−)-P-**28c** in $CHCl_3$

Heptalene	$[\alpha]^{20}_{546}$	$[\alpha]^{20}_{578}$
(+)-M-**16kA**	+1930 (c=1.03)	+1460 (c=1.03)
(+)-M-**16kB**	+1860 (c=0.92)	+1310 (c=0.92)
(+)-M-**32A**	+2550 (c=1.00)	+1910 (c=1.00)
(+)-M-**32B**	+2140 (c=0.51)	+1430 (c=1.03)
(−)-P-**23kA**	−1270 (c=0.99)	−980 (c=0.99)
(−)-P-**23kB**	−1420 (c=0.98)	−1100 (c=0.98)
(−)-P-**28c**	−1670 (c=0.10)	−1290 (c=0.10)

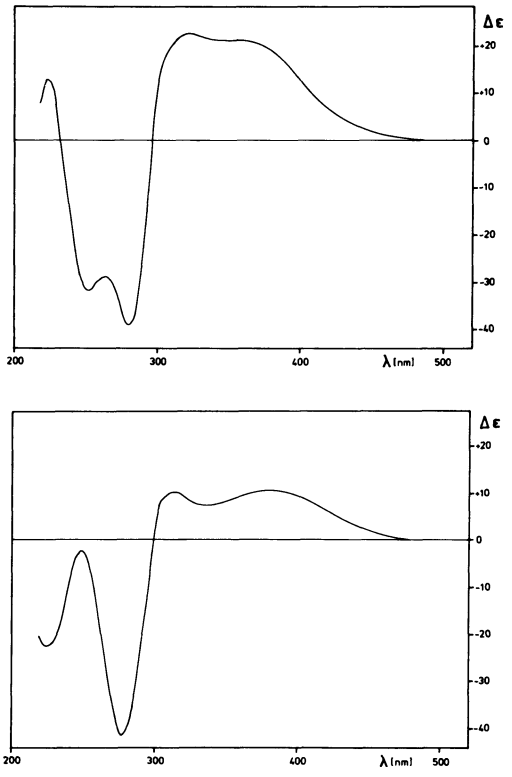
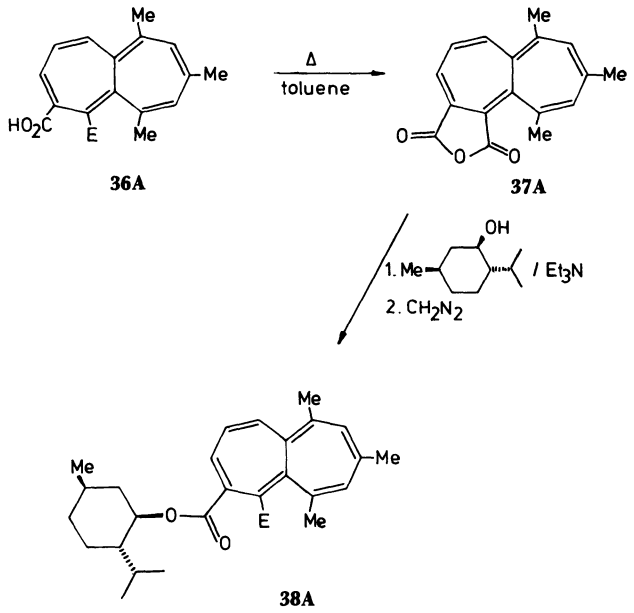


Fig. 1. CD-spectra of the heptalenes (+)-M-**32A** (top) and (+)-M-**32B** (bottom) in $CHCl_3$.

dicarboxylates **16k** and **27**, the chiroptical properties of the chiral heptalenes are caused mainly by the inherent chiral heptalene system and depend, only to a small degree, on the substituents.

The reaction of a mixture of rac-**23kA** and **B** with phosphorus pentachloride and subsequent reduction of the resulting dichloride rac-**24b** affords a mixture of the hexamethylheptalenes rac-**26A** and **B** in good yields. However, all attempts to prepare the enantiomerically pure (−)-P-**26** starting with the pure (−)-P-**23kA** or (−)-P-**23kB** have failed. Instead of the pure compounds, only mixtures of the bond shift isomers of **24k** and of **26** were obtained with specific optical rotations of at most 50, equivalent to an ee of at most 5%. A possible explanation for these results is that the chlorination of **23k** proceeds via an almost planar tropylium cation, which may also be responsible for the instability of the trimethyl derivative **24a**. In fact, the chlorination of **23kA** leads selectively to the bond shift isomer **24kB**, which then is acid-catalyzed equilibrated with the isomer **24bA**. This was shown by isolating the pure isomer **24bB** after quenching the reaction at −60 °C with $NaHCO_3$. A similar tropylium cation may also be responsible for the readily acid-catalyzed dehydration of the alcohols **23** to the aldehydes **27**. This reaction is also accompanied by a racemization. Thus, it is not possible to prepare enantiomerically pure methylheptalenes by this reaction sequence, starting with enantiomerically pure heptalene-1,2-dicarboxylates.[24,25] However, it has been shown recently that the optical resolution of the 1,5,6,10-tetramethylheptalene rac-**28c** can be carried out in good yields by HPLC on triacetylcellulose.[34] As expected, the chiroptical properties of the enantiomers of **28c** are very similar to those of the corresponding optically active heptalene carboxylates and diols.



Scheme 11.

The Dynamic Behavior of Chiral Heptalenes

The separation of the bond shift isomers and the resolution of the enantiomers of the dimethyl 5,6,8,10-tetramethylheptalene-1,2-dicarboxylate **16k** allowed for the first time a determination of the kinetic parameters of both the bond shift and the ring inversion of a substituted heptalene. According to the corresponding studies of cyclooctatetraenes,[9,11,12] this should provide information about the delocalized heptalene system and, therefore, about the antiaromaticity of this 12π-system. However, the energy barrier for the ring inversion of **16k** is considerably higher than that for the bond shift (Table 2). These results are inconsistent with planar transition states for both processes as proposed for the dynamic behavior of all cyclooctatetraenes investigated so far.[9,11] Rather the bond shift must occur via a nonplanar, helical chiral transition state. Therefore, it seems impossible to determine the delocalization energy for the antiaromatic systems from the difference of the activation enthalpies of both processes as done by Oth[9] and Paquette et al.[11] for cyclooctatetraene. Also for the hexamethylheptalene **26** the bond shift occurs with retention of the configuration, but both energy barriers are higher than those for the corresponding dicarboxylate **16k** (Table 2). This might be due to a larger steric hindrance of the spherical methyl groups in comparison with the ester groups. This assumption is corroborated by the fact that the value for the ring inversion, which requires an almost planar transition state, increases more than those for the bond shift. In order to obtain more detailed information about the geometries of the transition states, we calculated the dynamics of both processes for the substituted heptalenes **39**, **40**, **28a**, and **28c** having methyl groups in the peri-positions and also for the parent compound **5** by π-SCF-force field calculations.[35] According to these calculations, the bond shift of the

Table 2. Kinetic Parameters for the Bond Shift (BS) and the Ring Inversion (RI) of the Heptalenes **16k**, **26**, **28c**, and **38**.

Dynamic process	$\Delta H^{\ddagger}_{25°C}$/kcal mol^{-1}	$\Delta S^{\ddagger}_{25°C}$/e.u.
BS **16kB** → **16kA**	22.8±0.6	−11.1±2.0
BS **16kA** → **16kB**	25.7±0.6	−7.8±1.7
RI [(−)-**16kA** ⇄ (−)-**16kB**] → [rac-**16kA** ⇄ rac-**16kB**]	28.3±0.4	−11.6±0.9
RI [(−)-**38A** ⇄ (−)-**38B**] → [rac-**38A** ⇄ rac-**38B**]	20.4±0.3	−10.7±1.0
BS **26A** → **26B**	26.7±1.2	−4.4±3.3
RI [(−)-**26A** ⇄ (−)-**26B**] → [rac-**26A** ⇄ rac-**26B**]	36.7±2.1	1.9±4.6
RI (−)-**28c** → rac-**28c**	31.8±1.2	−4.9±2.6

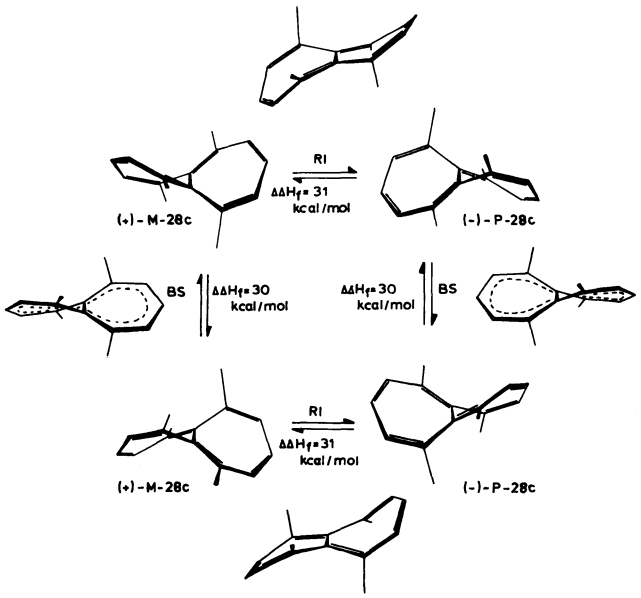
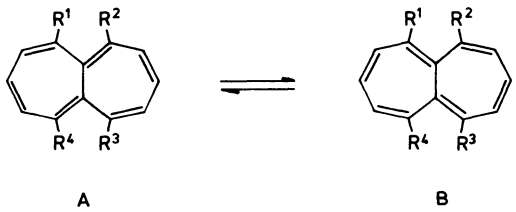


Fig. 2. Dynamic processes of 1,5,6,10-tetramethylheptalene **28c** (π-SCF-force field calculation).



	R^1	R^2	R^3	R^4
5	H	H	H	H
28a	Me	Me	H	H
28c	Me	Me	Me	Me
39	Me	H	H	H
40	Me	H	H	Me

Scheme 12.

1,5,6,10-tetramethylheptalene **28c** should occur via helical chiral, delocalized transition states with an activation enthalpy of 30 kcal mol^{-1}. On the other hand, the ring inversion should occur via partly planar, localized transition states with an activation enthalpy of 31 kcal mol^{-1} (Fig. 2). This value is in good agreement with recent experimental results (Table 2).[36] In contrast to this, planar transition states for both processes should require activation enthalpies of 62 and 72 kcal mol^{-1}, respectively. Therefore, the calculated conformations of the transition states seem to represent a good model for the dynamic behavior of highly substituted heptalenes. As the calculated values for the activation enthalpies for the dynamic processes (Table 3) indicate, the bond shift of the methylheptalenes **39**, **40**, and **28a** should also occur via nonplanar transition states. However, the difference of the activation enthalpies of both processes should decrease with the number of substituents. Furthermore, for heptalenes with two or less substituents in the peri-positions the ring inversion should be faster than the bond shift. While we could demonstrate that the bond shift of the (−)-menthyl heptalenecarboxylate **38** is not accompanied by racemization, we have not yet investigated the lower substituted heptalenes. However, the necessary data can be obtained by NMR measurements of heptalenes with diastereotopic substituents, i.e. the hydroxymethylheptalenes **23**. Similarily, Paquette et al.[11,12] found that the activation enthalpies of both dynamic processes for methyl-substituted cyclooctatetraenes were also dependend on the degree of substitution. While these authors explained this exclusively by the different steric interaction of the substituents in the assumed planar localized and delocalized transition states, our results for substituted heptalenes suggest that this may be due to different conformations of the transition states and, therefore, different steric strains of the ring system. In fact, calculations by Dewar et al.[37] suggest that the bond shift of cyclooctatetraene also proceeds via a nonplanar transition state.

Table 3. π-SCF-Force Field Calculations[35] of the Activation Enthalpies [kcal mol^{-1}] for Ring Inversion (RI) and Bond Shift (BS)

	Planar transition state		Nonplanar transition state	
	ΔH_{RI}	ΔH_{BS}	ΔH_{RI}	ΔH_{BS}
5	0.2	8.4	—[a]	—[a]
28a	23.9	33.0	19.4	19.6
28c	62.2	72.0	31.3	30.1
39	2.9[b]	13.6[d]	—[a]	13.2[d]
	6.2[c]	15.1[e]		14.6[e]
40	12.7[b]	20.8[d]	—[a]	18.4[d]
	14.4[c]	23.4[e]		21.1[e]

a) The planar transition state is energetically more favorable. b) (−)-P-A→(+)-M-A, c) (−)-P-B→(+)-M-B, d) A→B, e) B→A.

Conclusion

Our investigations of the dynamic behavior of chiral heptalenes established that the ring inversion and the bond shift, at least of highly substituted heptalenes, occur via nonplanar transition states with different conformations. Thus, it seems very questionable to determine the delocalization energies of heptalenes (even of the parent compound) from the difference of the activation parameters of both dynamic processes. The same should be valid for cyclooctatetraenes.

This work was generously supported by the Deutsche Forschungsgemeinschaft, the Fonds der Chemischen Industrie, and the Degussa A. G., Frankfurt/Main.

References

1) E. Hückel, *Z. Phys.*, **70**, 204 (1931); E. Hückel, *Z. Elektrochem.*, **43**, 752 (1937); E. Hückel, "Grundzüge der Theorie ungesättigter und aromatischer Verbindungen," Verlag Chemie, Berlin (1938).

2) D. Lloyd, "Nonbenzenoid Conjugated Carbocyclic Compounds," Elsevier, Amsterdam (1984); P. J. Garratt, "Aromaticity," J. Wiley & Sons, New York (1986).

3) J. A. Pople, *J. Chem. Phys.*, **24**, 111 (1956).

4) H. C. Longuet-Higgins, *Chem. Soc. Spec. Publ.*, No. 21, 109, (1967); J. A. Pople and K. G. Untch, *J. Am. Chem. Soc.*, **88**, 4811 (1966); F. Baer, H. Kuhn, and W. Regel, *Z. Naturforschung*, **22a**, 103 (1967).

5) R. Breslow, *Acc. Chem. Res.*, **6**, 393 (1973); M. J. S. Dewar, *Adv. Chem. Phys.*, **8**, 121 (1965).

6) K. Hafner, *Nachr. Chem. Tech. Lab.*, **28**, 222 (1980).

7) H. Irngartinger and M. Nixdorf, *Angew. Chem.*, **95**, 415 (1983); *Angew. Chem., Int. Ed. Engl.*, **22**, 403 (1983), and references cited therein.

8) B. Kitschke and H. J. Lindner, *Tetrahedron Lett.*, **1977**, 2511; P. Bischof, R. Gleiter, K. Hafner, K. H. Knauer, J. Spanget-Larsen, and H. U. Süss, *Chem. Ber.*, **111**, 932 (1978).

9) J. F. M. Oth, *Pure Appl. Chem.*, **25**, 573 (1971).

10) E. Vogel, H. Königshofen, J. Wassen, K. Müllen, and J. F. M. Oth, *Angew. Chem.*, **86**, 777 (1974); *Angew. Chem., Int. Ed. Engl.*, **13**, 732 (1974).

11) L. A. Paquette and J. M. Gardlik, *J. Am. Chem. Soc.*, **102**, 5033 (1980); L. A. Paquette, *Pure Appl. Chem.*, **54**, 987 (1982); L. A. Paquette, J. M. Gardlik, K. J. McCullough, R. Samodral, G. DeLucca, and R. J. Ouellette, *J. Am. Chem. Soc.*, **105**, 7649 (1983).

12) L. A. Paquette and J. A. Gardlik, *J. Am. Chem. Soc.*, **102**, 5016 (1980); L. A. Paquette, J. A. Gardlik, L. K. Johnson, and K. J. McCullough, *J. Am. Chem. Soc.*, **102**, 5026 (1980).

13) H. J. Dauben and D. J. Bertelli, *J. Am. Chem. Soc.*, **83**, 4659 (1961).

14) For reviews see: L. A. Paquette, *Isr. J. Chem.*, **20**, 233 (1980); G. Becker and H. Kolshorn in Houben-Weyl, "Methoden der Organischen Chemie," Vol. 5, part 2c, p. 418, Georg Thieme Verlag Stuttgart 1985.

15) H. J. Dauben and D. J. Bertelli, *J. Am. Chem. Soc.*, **83**, 4657 (1961).

16) E. Vogel, D. Kerimis, N. T. Allison, R. Zellerhoff, and J. Wassen, *Angew. Chem.*, **91**, 579 (1979); *Angew. Chem., Int. Ed. Engl.*, **18**, 545 (1979).

17) L. A. Paquette, A. R. Browne, and E. Chamot, *Angew. Chem.*, **91**, 581 (1979); *Angew. Chem., Int. Ed. Engl.*, **18**, 546 (1979); L. A. Paquette, A. R. Browne, E. Chamot, and J. F. Blount, *J. Am. Chem. Soc.*, **102**, 643 (1980).

18) E. Vogel and J. Ippen, *Angew. Chem.*, **86**, 778 (1974); *Angew. Chem., Int. Ed. Engl.*, **13**, 734 (1974).

19) E. Vogel and F. Hogrefe, *Angew. Chem.*, **86**, 779 (1974); *Angew. Chem., Int. Ed. Engl.*, **13**, 735 (1974).

20) K. Hafner, H. Diehl, and H. U. Süss, *Angew. Chem.*, **88**, 121 (1976); *Angew. Chem., Int. Ed. Engl.*, **15**, 104 (1976); W. Ude, Ph. D. thesis, TH Darmstadt 1980; G. L. Knaup, Ph. D. thesis, TH Darmstadt 1985.

21) W. Bernhard, H.-R. Zumbrunnen, and H.-J. Hansen, *Chimia*, **33**, 324 (1979).

22) F.-G. Klärner, B. Dogan, W. R. Roth, and K. Hafner, *Angew. Chem.*, **94**, 721 (1982); *Angew. Chem., Int. Ed. Engl.*, **21**, 701 (1982).

23) K. Hafner and G. L. Knaup, *Tetrahedron Lett.*, **27**, 1673 (1986); see also: 21) and W. Bernhard, P. Brügger, J. J. Daly, G. Englert, P. Schönholzer, and H.-J. Hansen, *Helv. Chim. Acta*, **68**, 1010 (1985).

24) K. Hafner and G. L. Knaup, *Tetrahedron Lett.*, **27**, 1665 (1986).

25) K. Hafner, N. Hock, G. L. Knaup, and K.-P. Meinhardt, *Tetrahedron Lett.*, **27**, 1669 (1986).

26) K. Hafner and K.-P. Meinhardt, unpublished results.

27) H. J. Lindner and B. Kitschke, *Angew. Chem.*, **88**, 123 (1976); *Angew. Chem., Int. Ed. Engl.*, **15**, 106 (1976); J. Stegemann and H. J. Lindner, *Tetrahedron Lett.*, **1977**, 2515.

28) J. F. M. Oth, K. Müllen, H. Königshofen, J. Wassen, and E. Vogel, *Helv. Chim. Acta*, **57**, 2387 (1974).

29) F. G. Klärner, private communication; B. M. J. Dogan, Ph. D. thesis, Bochum 1983.

30) K. Hafner, G. L. Knaup, H. J. Lindner, and H.-C. Flöter, *Angew. Chem.*, **97**, 209 (1985); *Angew. Chem., Int. Ed. Engl.*, **24**, 212 (1985).

31) The bond shift isomers **16kA** and **16kB** were also synthesized and seperated by H.-J. Hansen et al. (W. Bernhard, P. Brügger, J. J. Daly, P. Schönholzer, R. H. Weber, and H.-J. Hansen, *Helv. Chim. Acta*, **68**, 415 (1985); W. Bernhard, P. Brügger, P. Schönholzer, R. H. Weber, and H.-J. Hansen, *Helv. Chim. Acta*, **68**, 429 (1985), but these authors originally postulated the structure of dimethyl 3,6,8,10-tetramethylheptalene-1,2-dicarboxylate for **16kB** and a new rearrangement of the heptalene skeleton for the interconversion **A**⇄**B** (H.-J. Hansen, lecture at the ETH Zürich, January 21, 1985; W. Bernhard, Ph. D. thesis, Fribourg/Switzerland 1982; P. Brügger, Ph. D. thesis, Fribrourg/Switzerland 1983).

32) A. Manschreck, unpublished results.

33) G. L. Knaup and K. Hafner, unpublished results; see also R. H. Weber, P. Brügger, T. A. Jenny, and H.-J. Hansen, *Helv. Chim. Acta*, **70**, 742 (1987).

34) G. Blaschke, unpublished results.

35) H. J. Lindner, *Tetrahedron*, **30**, 1127 (1974); Program PIMM82, unpublished, TH Darmstadt, 1982; H.-C. Flöter, Ph. D. thesis, TH Darmstadt 1987.

36) K. Hafner and N. Hock, unpublished results.

37) M. J. S. Dewar, A. Harget, and E. Haselbach, *J. Am. Chem. Soc.*, **91**, 7521 (1969).