78. Light-Induced, Thermal, and Acid-Catalyzed π-Skeletal Rearrangements of Five-Ring-Annelated Heptalenes[1])

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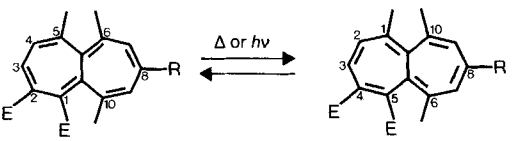
(23. II. 87)

It is shown that, upon irradiation in $CDCl_3$ solution, 5,6,8,10-tetramethylheptalene-1,2-dicarboxylic anhydride (**6**) rearranges to its double-bond-shift (DBS) isomer **7** in an equilibrium reaction (*Scheme 2*). The isomer **7** is DBS stable at −50°. At *ca.* 30°, a thermal equilibrium with 97.8% of **6** and 2.2% of **7** is rapidly established. Similarly, the *'ortho'*-anhydrides **9** and **11** (*Schemes 4* and *5*) can be rearranged to their corresponding DBS isomers **12** and **13**, respectively. Whereas **12** is DBS stable at 30° (at 100° in tetralin, 94.0% of **9** are in equilibrium with 6.0% of **12**), the i-Pr-substituted isomer **13** is already at 30° in thermal equilibrium with **11** leading to 98.7% of **11** and 1.3% of **13**. It is shown by rearrangement of diasteroisomeric *'ortho'*-anhydrides of known relative and absolute configuration (*Scheme 6*) that the DBS in such five-ring-annelated heptalenes occurs with retention of the configuration of the heptalene skeleton as already established for other heptalene compounds. It is found that the DBS process may also take place under acid catalysis (*e.g.* HCl/CH_3OH), thus yielding **9** from **12** (*Scheme 9*). The *'ortho'*-anhydrides **21** and **23** (*Scheme 10*) which are isomeric with **9** and **11** (*Scheme 3*) undergo rapid DBS' already at room temperature. The thermal equilibrium **21**⇄**22** consists of 18% of **21** and 82% of **22** at 30° and that of **23**⇄**24** of 17% of **23** and 83% of **24** at −30°. From these equilibrium mixtures, the pure DBS isomer **22** can be obtained by crystallization. Again, these rapid DBS' occur with retention of configuration of the heptalene skeleton (*Fig. 4*).

1. Introduction. – Recently, we have shown that the thermal as well as the light-induced π-skeletal rearrangement of heptalenes such as **1** and **2** (*Scheme 1*) occurs with retention of the configuration of the C_2-twisted heptalene skeleton [1] (*cf.* also [2]). This

Scheme 1



1[4]) **a** R = CH_3, E = $COOCH_3$ **2**[4])
b R = *t*-C_4H_9, E = $COOCH_3$

[1]) Presented in part by *H.-J. H.* in a lecture at the ETH in Zürich, 1985.
[2]) Part of the planned Ph. D. thesis of *R.H.W.*, University of Basel, Switzerland.
[3]) Part of the Ph. D. thesis of *P.B.*, No. 858, University of Fribourg, Switzerland, 1983.
[4]) C-Atom numbering of the heptalene derivatives **1**,**3**,**6**, and **8** conforms to the IUPAC-rules. The special C-atom numbering of the corresponding DBS isomers **2**, isomer of **3**, **7**, and **16** is nonsystematic and has been chosen in order to distinguish these compounds easily from **1**,**3**,**6**, and **8**. C-Atom numberings and names of all other furo-annelated heptalene derivatives are in accordance with IUPAC nomenclature of *bridged heterocycles* instead of *fused heterocycles*, thus allowing a facile distinction between the corresponding DBS isomers.

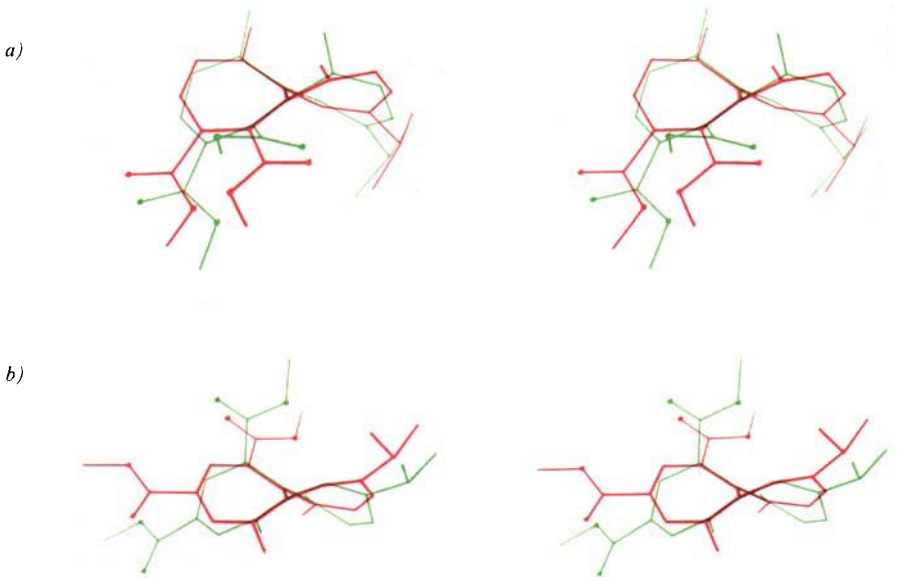


Fig. 1. *Stereographic representation of the structure of* a) **3** *and* b) **4** *superimposed by the corresponding hypothetical transition states for the DBS, computer-generated from the ground-state skeletons under* D_2*-symmetry constraints* (ground-state structures in green, transition-state structures in red)

finding indicates that the highest possible symmetry the heptalene skeleton can attain at the transition state of these double-bond shifts (DBS) is D_2 (*cf.* [1]). Thus, the *'peri'*-substituents at C(1), C(5), C(6), and C(10) will approach but not pass each other in the transition state of the DBS. The passing of the substituents would lead to an inversion of the configuration of the heptalene skeleton which occurs at higher temperature than the thermal DBS process [1] [3] (*cf.* also [2]). The approach of the *'peri'*-substituents can be described as a reduction of the torsion angles of C–C bonds with C(5a) or C(10a) as common atom. This is visualized in *Fig. 1* which shows a stereographic view of dimethyl 7-isopropyl-5,10-dimethylheptalene-1,2-dicarboxylate (**3**; see *Table 1*) and dimethyl 9-isopropyl-1,6-dimethylheptalene-3,5-dicarboxylate (**4**) according to their X-ray structure analysis (*cf.* [4]) and, derived from these structures, the corresponding hypothetical, computer-generated (*cf.* [5]) D_2-like transition states for the DBS. The flattening of the heptalene skeleton in the postulated DBS transition state can clearly be recognized[5]). From this follows that a minimization of the torsional angles of the heptalene skeleton already in the ground state will favor the DBS process. This is, indeed, in general the case when the number of substituents at the *'peri'*-positions is reduced (see lit. cit. in [1][6])).

The $COOCH_3$ substituents at C(1) and C(2) in **1** and **3** can easily be transformed *via* the COOH functions into the cyclic 1,2-anhydrides [3]. *Table 1* shows a comparison of

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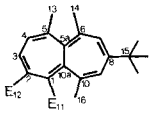
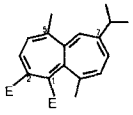
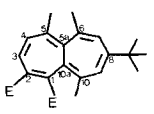
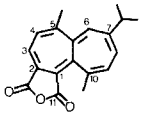
[5]) The distance of the C=O C-atoms of the $COOCH_3$ group at C(1) or C(5) and the CH_3 group at C(10) or C(6) amounts to 3.25 and 3.38 Å, respectively, for the ground-state structures **3** and **4**, and to 2.99 and 2.92 Å, respectively, for the corresponding D_2-like transition states, *i.e.* the reduction of the distances amounts to *ca.* 8 and 14%, respectively, in the DBS transition state.

[6]) A further effect on the transition state of the DBS will be exerted by the electron-acceptor or -donor property of the substituents at the heptalene ring (see later as well as [6]).

Table 1. *Relevant Structural Data of Heptalenes*[a])

				
Torsion angles [deg]	**1b**	**3**	**2b**[b])	**5**
C(10), C(10a), C(1), C(11)[c])	–2.4	–8.1	–67.7	–19.2
C(1), C(10a), C(10), C(16)	–60.9	–61.4	–8.2	–54.2
C(6), C(5a), C(5), C(13)	64.2	–53.2	–7.9	–56.6
C(5), C(5a), C(6), C(14)	–9.6	–	–69.9	–
C(5), C(5a), C(10a), C(1)	64.0	63.0	64.6	55.1
C(6), C(5a), C(10a), C(10)	65.7	62.4	62.6	55.3
C(10a), C(1), C(2), C(3)	–31.0	–33.5	3.2	–25.5
C(5a), C(6), C(7), C(8)	–34.0	–34.2	3.8	–28.0
Bond angles [deg]				
C(10a), C(1), C(2)	123.8	123.8	120.9	129.2
C(5a), C(6), C(7)	123.7	126.7	120.1	127.7
C(1), C(2), C(3)	124.9	124.7	124.0	128.7
C(6), C(7), C(8)	128.0	122.3	126.5	123.7

[a]) Taken from the corresponding X-ray structure analyses: see [1], for **1b** and **2b**, see [4] for **3**, and *cf. Footnote 3* for **5**.

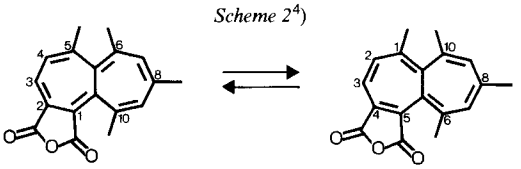
[b]) For an easy comparison, the C-atom numbering of **2b** has been chosen as for **1b**.

[c]) Number of the C-atom of the C=O group at C(1) (see X-ray structures).

structural features of the heptalenes **1b**, **2b**, and **3** with those of the cyclic 1,2-anhydride **5** of **3**. As can be seen, the annelation of the five-membered anhydride ring leads, in general, to a flattening of the heptalene structure (*cf.* the torsion angles of the C(5a)–C(10a) bond and of the C(1)=C(2) and the corresponding C(6)=C(7) bond). Moreover, in **5** the C(1)=C(10a) bond already exhibits a strong torsion of the same sense as expected for its DBS isomer (*cf.* the corresponding sense of torsion in **1b** and **3** in comparison to **2b**) which also should lower the energy difference between the ground and the transition state of the DBS. Therefore, we were interested to study the DBS in heptalenes annelated with a five-membered ring at the C(1)–C(2) bond which would also allow to investigate the position of the thermal equilibrium of corresponding DBS isomers. The DBS isomers **1a**, **1b** and **2a**, **2b** are separated at 100° by $\Delta G_{373} = -6.4$ and -6.6 kJmol^{-1}, respectively [1].

2. Results. – 2.1. *Thermal and Light-Induced Isomerizations of the Anhydrides* **5**–**7**. Careful inspection of a 400-MHz ^{1}H-NMR spectrum of *rac*-5,6,8,10-tetramethylheptalene-1,2-dicarboxylic anhydride (**6**) in $CDCl_3$ showed that a second compound was present (to an extent of 2.2%) with the same number of signals, however, distinctly shifted to higher field and with alterations in coupling constants. Especially indicative was ^3J = 11.4 Hz of an *AB* system at 6.70 and 7.00 ppm which corresponded to that of H–C(3) and H–C(4) at 7.35 and 6.60 ppm in **6** with ^3J = 6.5 Hz [1]. So, there was little doubt left that the second compound must be the DBS isomer of **6**, namely *rac*-1,6,8,10-tetramethylheptalene-4,5-dicarboxylic anhydride (**7**; *Scheme 2*). Irradiation of a solution of **6** in $CDCl_3$ at –60° with a high-pressure Hg lamp followed by an immediate 360-MHz NMR measurement at –50° confirmed the presence of **7**. Increase of the signals of **7** had been observed, and a mixture of 58% of **6** and 42% of **7** had been formed at the end

Scheme 2[4])



(*Fig. 2*)[7]). Typical for the structure of **7** is – in addition to the aforementioned $^3J(2,3) = 11.4$ Hz – the presence of two CH_3 signals at 2.04 and 2.01 ppm with allylic coupling constants of 1.2 and 1.4 Hz, respectively, in contrast to the structure of **6** which possesses three CH_3 groups of this type (*cf. Fig. 2* and [1] [3] [4]). Further proof for the structure of **7** was obtained from the observation that warming up of the NMR solution of **6** and **7** to *ca.* 30° led to the original mixture of 97.8% of **6** and 2.2% of **7**. Thus, at 30° both DBS isomers are separated by $\Delta G_{303} = -9.6 \pm 0.1$ kJmol^{-1}, and the DBS process is fast at this temperature[8]). On the other hand, (–)-**6** is configurationally stable for a longer

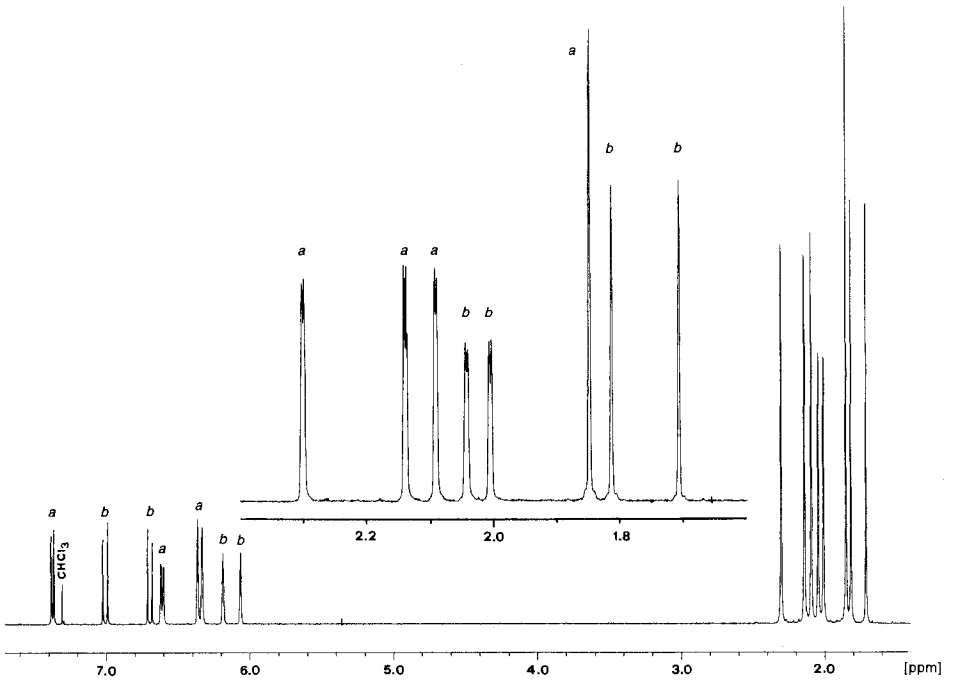


Fig. 2. *^{1}H-NMR spectrum* (360 MHz, $CDCl_3$) *of* **6** *at –50° after UV/VIS irradiation at –60° indicating the presence of its DBS isomer* **7**. The signals of **6** are marked with *a* that of **7** with *b*; $CHCl_3$ at 7.30 ppm.

[7]) As already observed for heptalenedicarboxylic esters such as **1** and **2** [1], all heptalenes, so far investigated, are completely DBS-stable on irradiation in the crystalline state.

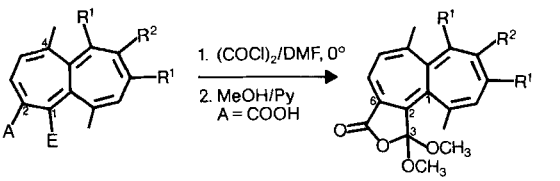
[8]) Only in one case, we have determined the temperature dependence of the thermodynamic and kinetic parameters of the equilibrium process reported here (see later; *Scheme 10*). Therefore, 'fast' means qualitatively $\tau_{1/2} < 1$ min for the equilibrium process ($k_1 + k_{-1}$) at a given temperature.

period at room temperature as we have already reported [3]. This means that the DBS in the cyclic five-membered anhydrides **6** and **7** must occur *via* a transition state different from that leading to racemization, *i.e.* presumably *via* a D_2-like transition state.

The i-Pr-substituted 1,2-dicarboxylic anhydride **5** (*cf. Table 1*) showed, at −50° in $CDCl_3$, no detectable additional signals in its 360-MHz ^{1}H-NMR spectrum. Also irradiation at this temperature, or heating and cooling of the probe did not lead to the appearance of further signals. From these observations, we can conclude that the thermal equilibrium of **5** with its DBS isomer is far on the side of **5**, *i.e.* ΔG_{303} must be > -12 kJmol^{-1}, since otherwise $\geqq 1\%$ of the DBS isomer of **5** would have been detected in our ^{1}H-NMR measurements, and we see no reasons for an obstruction of the thermal or light-induced DBS process in **5**. It seems much more reasonable that the DBS process is already comparably fast at −50° so that the DBS isomer of **5** could not be accumulated photochemically even at this temperature[9]).

2.2. *Synthesis of* Stadler *Compounds* **9** *and* **11**, *and Thermal and Light-Induced Isomerizations of* **9**, **11**, *and* **14** *to* **12**, **13**, *and* **15**, *Respectively*. We have already reported briefly

Scheme 3



8 $R^1 = CH_3$, $R^2 = H$
10 $R^1 = H$, $R^2 = i\text{-}C_3H_7$
A = COOH
E = $COOCH_3$

9 (83%) $R^1 = CH_3$, $R^2 = H$
11 (63%) $R^1 = H$, $R^2 = i\text{-}C_3H_7$

that the methyl hydrogen dicarboxylate **8** of **1a** yielded upon reaction with oxalyl chloride and DMF followed by treatment with MeOH in pyridine, the corresponding cyclic 1,2-anhydride dimethyl acetal **9**, isomeric with **1a** [3]. Similarly, the methyl hydrogen dicarboxylate **10** of **3** gave, under the same conditions, the cyclic anhydride dimethyl acetal **11**, isomeric with **3** (*Scheme 3*)[10]). Both *Stadler* compounds are stable with respect to light-induced DBS′ in the crystalline state. However, in a solution of *tert*-butyl methyl ether (*t*-BuOMe), on irradiation with the Hg lamp, the CH_3-substituted **9** was rapidly transformed into a photostationary mixture with its DBS isomer **12**, consisting of 41% of **9** and 59% of **12** (*Scheme 4*). The isolated isomer **12** is stable at room temperature

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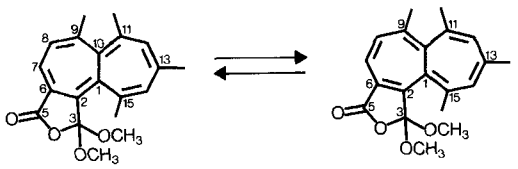
[9]) Our technique allowed irradiation experiments only at −60° and measurements in the NMR spectrometer at −50° as the lowest temperature. At these temperatures, the dimethyl ester **3** (*cf. Table 1*), derived from **5**, reacts only sluggishly on irradiation. After 30 min of irradiation, a second compound was formed to an extent of *ca.* 5% which might represent the DBS isomer of **3** according to 2*s* for the CH_3 groups at C(1) and C(6) (1.68 and 1.77 ppm, respectively) and a *d* (^3J = 11.7 Hz) for H–C(2). Most of the other ^{1}H-NMR signals were hidden under the signals of **3**. At *ca.* 30°, the second compound of **3** could not be detected in a 360-MHz ^{1}H-NMR spectrum, *i.e.* ΔG_{303} between **3** and its DBS isomer must be $\geqq -12$ kJmol^{-1}.

[10]) We will report on this new reaction in detail later [7]. Since we adopted the conditions for the reaction from a method described by *Stadler* [8] for the rapid and mild esterification of alcohols and acids, including protected amino acids, we call compounds of type **9** and **11** *Stadler* compounds.

Scheme 4

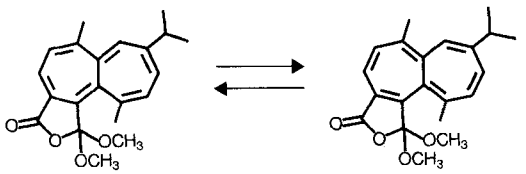


9 41% 94.0% | *hv*, *t*-BuOMe (20°) 100°, tetralin | **12** 59% 6.0%

and forms pale yellow crystals. On irradiation in *t*-BuOMe, **12** was also transformed into the photostationary mixture **9**/**12**. Also on heating in tetralin above 80°, both **9** and **12** were interconvertible. The thermal equilibrium mixture consisted of 94.0% of **9** and 6.0% of **12** at 100° which corresponds to a $\Delta G_{373} = -8.5$ kJmol^{-1} [11]).

The i-Pr-substituted *Stadler* compound **11** showed no visible alteration on irradiation in *t*-BuOMe at room temperature or on heating in tetralin at 100°. However, when cooled to −60° in $CDCl_3$ solution and irradiated, the formation of the DBS isomer **13** to up to 83% could easily be observed (*Scheme 5*)[12]). Warming up of the $CDCl_3$ solution to *ca.* 30° restored the nearly exclusive presence of **11**. Careful inspection of the 360-MHz ^{1}H-NMR spectra, however, showed that there was a persistent presence of 1.3 ± 0.3% of the DBS isomer **13** at 30° which corresponds to $\Delta G_{303} = -11 \pm 1$ kJmol^{-1}.

Scheme 5[4])



11 17% 98.7% | *hv*, $CDCl_3$ (−60°) *ca.* 30°, $CDCl_3$ | **13** 83% 1.3 ± 0.3%

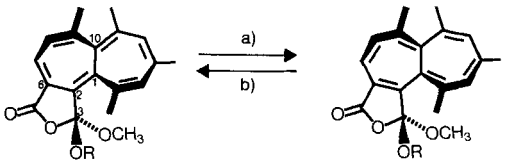
To demonstrate that the DBS process in *Stadler* compounds like **9** and **11** to give **12** and **13**, respectively, occurs with retention of configuration of the heptalene skeleton as observed for all other heptalene structures so far investigated, we irradiated the diastereoisomeric *Stadler* compounds **14A** and **14B** whose relative (*PM*,*SR*)- and (*PM*,*RS*)-configurations (see *Scheme 6*) had been established by an X-ray structure analysis of **14A** [3]. The results were unequivocal: **14A** yielded, on irradiation, nearly exclusively **15A** and **14B** its DBS isomer **15B** (*Scheme 6*)[13]). Similarly, heating of **15A** in tetralin at 100° for 1 h

[11]) The thermal equilibrium mixture of the diesters **1a** and **2a**, which are isomeric with **9** and **12**, consisted of 88.7% of **1a** and 11.3% of **2a** at 100° [1].

[12]) See *Exper. Part* for the unambiguous ^{1}H-NMR characterization of its structure.

[13]) Compounds **15A** and **15B** were well separated from each other as well as from **14A** and **14B** on TLC. Thus, traces of the diastereoisomer **15B** could easily be detected in the presence of **15A**. The TLC analysis of the mixture of DBS isomers obtained after irradiation of **14A** showed that **15A** was the predominant product, and **15B** had only been formed, if at all, in traces (see *Exper. Part*).

Scheme 6



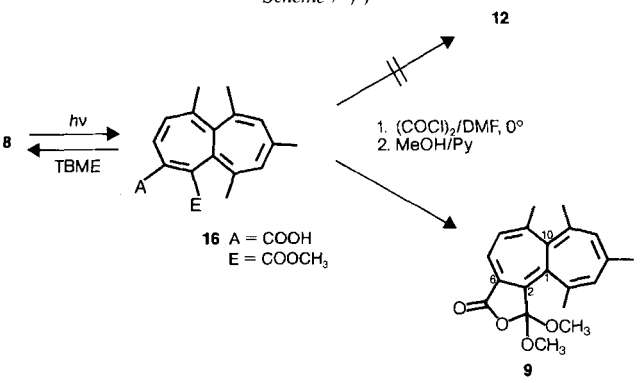
14A R = (*S*)-PhCH(CH$_3$)[c] **15A**
14B R = (*R*)-PhCH(CH$_3$)[c] **15B**

a) *hv*, *t*-BuOMe, 20°.
b) Δ, tetralin, 100°.
c) Only the (*P*,*S*)- and (*P*,*R*)-enantiomers, respectively, are shown.

led to nearly complete transformation (> 95%) into **14A**; the diastereoisomeric DBS isomer **14B** could not be detected. An X-ray structure analysis of **15A** indicated, indeed, also the (*PM*,*SR*)-configuration as derived for **14A** (*cf.* [7]). Thus, the DBS process in **14A** and **14B** occurs again with retention of the configuration of the heptalene skeleton. These results were further corroborated by the light-induced rearrangement of (−)-**14A** into (−)-**15A** which showed nearly no change of its ORD spectrum in comparison with that of (−)-**14A** (see [3] and *Exper. Part*).

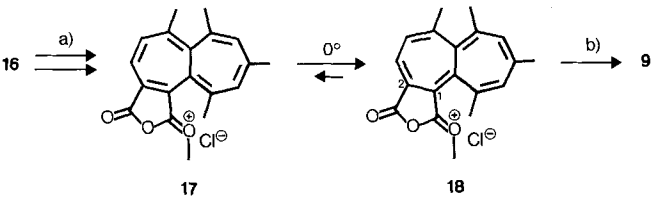
Since the Me-substituted *Stadler* compounds turned out to be DBS stable up to 80°, we looked for an independent synthesis of compound **12** in a way that we first photoisomerized the methyl hydrogen dicarboxylate **8** (*cf.* [1]) to its DBS isomer **16** which was then subjected to the *Stadler* conditions. However, to our surprise, the only isolable product of this reaction was not **12** but its DBS isomer **9** (*Scheme 7*). No doubt, an intermediate must have been passed in the course of the reaction which allowed a rapid DBS process already at 0° and which is energetically more stable in its DBS form corresponding to **9**. We supposed that the postulated intermediates were the charged

Scheme 7[a])[4])



a) See also *Scheme 3;* **16** can be obtained more easily by the light-induced isomerization of **1a** into **1b** and semi-saponification of the latter.

Scheme 8



a) $(COCl)_2$/DMF, 0°. b) MeOH/Py, 0°.

O-methylated cyclic anhydrides **17** and **18** (*Scheme 8*)[10][14]). The first one can be generated by cyclization of the primarily formed *Stadler* intermediate with oxalyl chloride and DMF[15]). Trapping of **18** with MeOH in pyridine will then lead to the predominant formation of **9** depending on the equilibrium mixture of **17** and **18**. The *O*-demethylated anhydrides **6** and **7** will offer a good structural model for **17** and **18**. Therefore, we can expect that **18** and **17** are separated at 0° by $\Delta G \geqq -10$ kJmol^{-1} (*i.e.* < 2% of **17** will be in thermal equilibrium with **18**, assuming that ΔS is negative; *cf.* [1]).

2.3. *Acid-Catalyzed Isomerization of* **12**. On the base of the above-mentioned facts and observations, we can now define the prerequisites for an acid-catalyzed π-skeletal rearrangement of heptalenes such as the *Stadler* compounds **12** (*Scheme 4*) and **13** (*Scheme 5*). It can be assumed that these cyclic anhydride dimethyl acetals will undergo an acid-catalyzed transacetalization in the presence of a strong acid like HCl in alcoholic solution *via* intermediates of type **17** and **18**. As long as k_{ADD} and k_{DBS} [16]) are of comparable size at a given temperature, an acid-catalyzed DBS process should be observable. This is indeed the case (*Scheme 9*). Whereas the *Stadler* compound **9** was largely stable during

Scheme 9

12	$\xrightarrow[20°]{HCl/CD_3OD}$	[^{2}H]-**12**	+	[^{2}H]-**9**	+	[^{2}H]-**2a**	+	[^{2}H]-**1a**
Yields after[a]) 3 h		72%		13%		9%		+[b])
Isotopic composition[c])	$^2H_6$	5%[d])		14%		12%		
	$^2H_3$	34%		63%		88%		
	$^2H_0$	61%		23%		< 1%		
Yields after[a]) 2 d		18%		27%		28.5%		26.5%
Isotopic composition[c])	$^2H_6$	92%		92%		56%		74%
	$^2H_3$	8%		8%		44%		26%

[a]) Yields of isolated material. [b]) Traces of **1a** were formed according to TLC. [c]) $^2H_6$: 2 C[$^2H_3$]O. $^2H_3$: C[$^2H_3$]O/CH_3O. $^2H_0$: 2 CH_3O as determined by MS. [d]) ^{1}H-NMR Measurements indicated a global ^{2}H-content of 1.2 ^{2}H/molecule which corresponds well with the MS data: 1.3 ^{2}H/molecule.

[14]) A further proof for the intervention of such *O*-methylated cyclic anhydride structures can be found in the fact that, in the presence of alcohols, sterically crowded in the α-position, the formation of an increasing amount of the *O*-demethylated cyclic anhydride **6** is observed (*cf.* [3]).

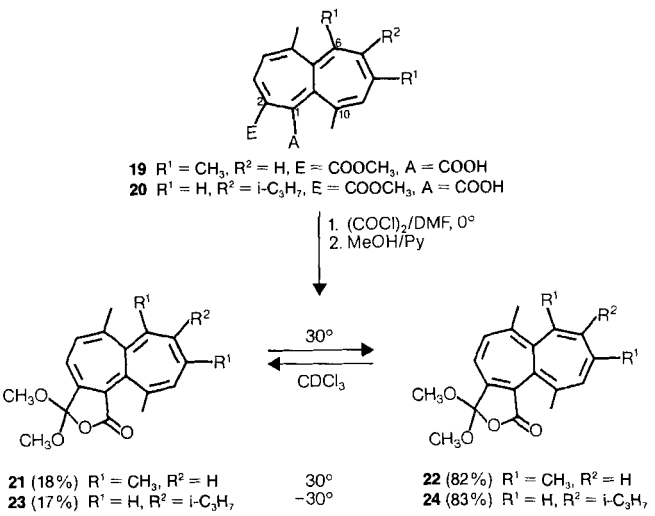
[15]) At the moment, we cannot definitely exclude the possibility that the DBS occurs already to some extent in the primarily formed open-chain *Stadler* intermediate, and that cyclization can only occur in its more flexible (with respect to torsion around the C(1)–C(2) bond) DBS isomer exclusively leading to the formation of **18** which is then trapped by MeOH.

[16]) k_{ADD} stands for the global rate constant for the alkoxy-group exchange on the α- and β-site of the heptalenes. k_{DBS} is the sum of the rate constants ($k_1 + k_{-1}$) for the discussed equilibrium process.

8 days in methanolic HCl (*ca.* 20 mol-% with respect to **9**) at room temperature in the dark[17]), its DBS isomer **12** was mainly transformed into **9** and into comparable amounts of the dimethyl esters **2a** and **1a** already after 2 days. The experiment with HCl/CD_3OD showed that the MeO groups at C(3) were nearly completely exchanged in **12** and **9**. On the other hand, the two isomeric dimethyl esters [^{2}H]-**2a** and [^{2}H]-**1a** possessed a distinctly different degree of MeO-group exchange. Since both esters do neither undergo an acid-catalyzed MeO-group exchange nor the DBS under the applied condition, the different 2 C[$^2H_3$]O/C[$^2H_3$]O ratios can be interpreted as a 'memory effect' of the DBS process occurring in the postulated charged intermediates. The higher exchange ratio of [^{2}H]-**1a** reflects the fact that its precursor **9** must have taken up necessarily a C[$^2H_3$]O group after the DBS process leading to **18**. The ester [^{2}H]-**2a**, however, at the beginning of the reaction, can be formed from **12** free of C[$^2H_3$]O[18]). These interpretations are supported by the results of a treatment of **12** with HCl/CD_3OD during 3 h (*Scheme 9*). The rearranged *Stadler* compound [^{2}H]-**9** consists of 63% of molecules carrying a C[$^2H_3$]O group as a result of the fact that the rearranged intermediate **18** is mainly trapped by CD_3OD[19]).

2.4. Stadler *Compounds* **21/22** *and* **23/24**. When the methyl hydrogen dicarboxylates **19** and **20** [3], isomeric with **8** and **10** (*cf. Scheme 3*), were reacted with oxalyl chloride and

Scheme 10



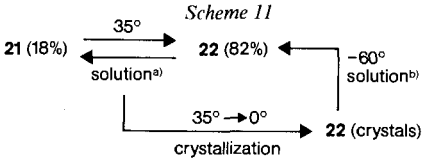
[17]) The dimethyl ester **1a** was formed in small amounts, but no **2a** or **12** (TLC).

[18]) We suppose that the dimethyl esters **1a** and **2a** are formed from their *Stadler* precursors **9** and **12** by hemiacetalization of the free C=O group. This view is supported by the fact that [^{2}H]-**2a**, isolated from the reaction of **12** with HCl/CD_3OD during 3 h, consisted mainly of [$^2H_3$]-**2a** and [$^2H_6$]-**2a**, but not of **2a** (*e.g.* in contrast to rearranged [^{2}H]-**9** which still contained 23% **9**; *cf. Scheme 9*).

[19]) It was shown in separate exchange experiments (see *Exper. Part*) that the rate of the MeO group exchange is the same for both *Stadler* compounds. The fact that the rearranged [^{2}H]-**9** contains after 3 h in HCl/CD_3OD still 23% of **9**, *i.e.* non-exchanged molecules, indicates that the DBS must occur in part in a tight charged complex between **17** (*Scheme 8*) and CH_3OD, in which CH_3OD cannot be exchanged by the surrounding CD_3OD molecules. Another, less probable explanation would be that the DBS process can also occur in species protonated at the oxo group at C(5).

DMF, followed by addition of MeOH in pyridine the *Stadler* compounds **21**/**22** and **23**/**24**, respectively, were obtained (*Scheme 10*). The ^{1}H-NMR analysis of the reaction mixtures in $CDCl_3$ at 30° revealed that in both cases the DBS isomers **22** and **24** with a C=C bond at the annelation site of the furan moiety were preponderant. Whereas the ^{1}H-NMR (400 MHz) signals of **21** and **22** in $CDCl_3$ were sharp and clearly separated at

Scheme 11



a) Et_2O/hexane. b) $CDCl_3$.

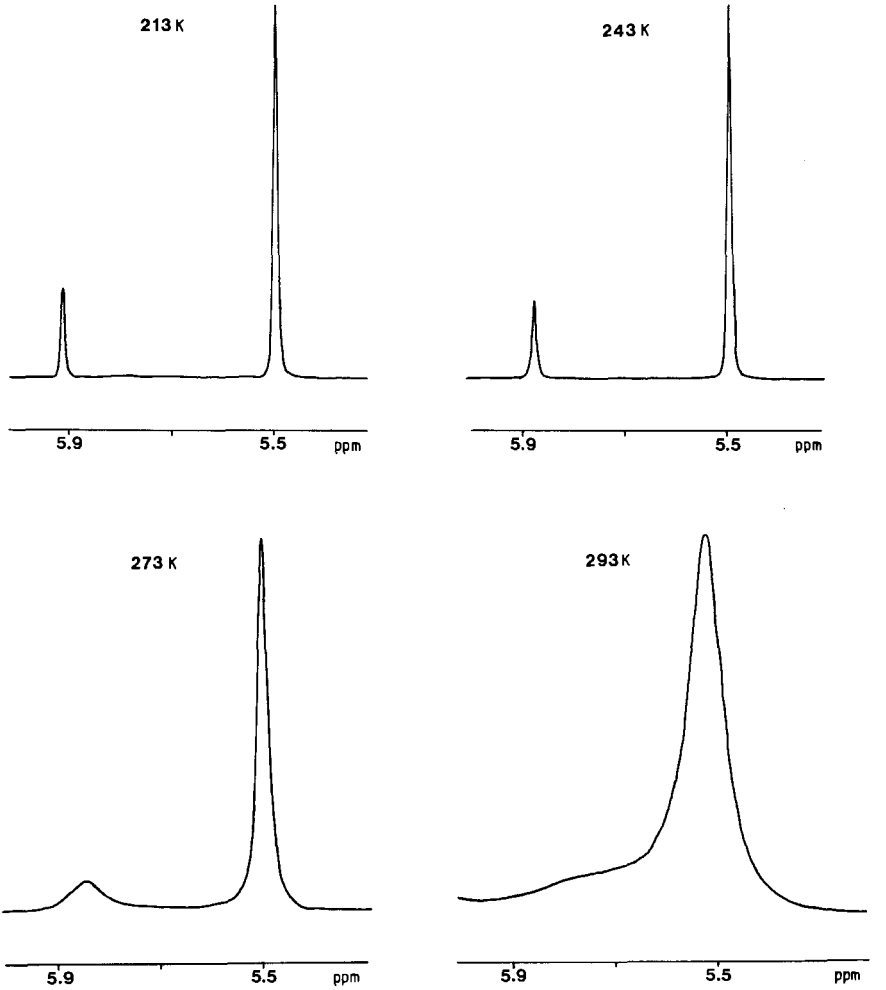


Fig. 3. *Section of the ^{1}H-NMR spectrum* (360 MHz, $CDCl_3$) *of* **23**/**24** *showing the temperature dependence of the signals of H–C(11) in* **23** (*ca.* 5.9 ppm) *and* **24** (*ca.* 5.5 ppm)

30° and also at 60° (*i.e.* coalescence well above 60°), the signals of **23** and **24** were broad and showed just coalescence at *ca.* 25°. However, at −30°, the ^{1}H-NMR signals of **23** and **24** became also sharp and clearly separated. On the other hand, both mixtures crystallized nicely from Et_2O/hexane in dark red needles in nearly quantitative yield. Since we could detect only one form of crystals, we suspected that only one DBS isomer was present. Indeed, when the crystals obtained from the solution of **21**/**22** were precooled to −60° and dissolved in precooled $CDCl_3$ at −60°, only the ^{1}H-NMR (360 MHz) signals of **22** could be found. Warming up to *ca.* 30° restored the original 18:82 mixture **21**/**22** (*Scheme 11*). Thus, **21** and **22** are separated by $\Delta G_{303} = 3.8$ kJmol^{-1} [20]).

In the ^{1}H-NMR spectrum of **23** and **24** (5% solution in $CDCl_3$), H−C(11) appeared as well separated broad *s* below 273 K which coalesced at *ca.* 298 K (*Fig. 3*). Integration of both signals in the range of 213–253 K (see *Table 2*, *Exper. Part*) yielded the temperature dependence of ΔG with $\Delta H° = 1.8 \pm 0.4$ kJmol^{-1}, $\Delta S° = -5.4 \pm 1.7$ JK^{-1} mol^{-1} and $\Delta G_{303} = 3.4 \pm 0.9$ kJmol^{-1}, in good accord with the corresponding value for the equilibrium **21**⇄**22**. Taking into account this temperature dependence of the population ratio **24**/**23**, the line-shape analysis for H−C(11) yielded, for the global equilibrium process ($k_1 + k_{-1}$), $\Delta H^{\neq} = 50 \pm 2$ kJmol^{-1}, $\Delta S^{\neq} = -23 \pm 6$ JK^{-1}mol^{-1} and $\Delta G^{\neq}_{298} = 57 \pm 6$ kJ

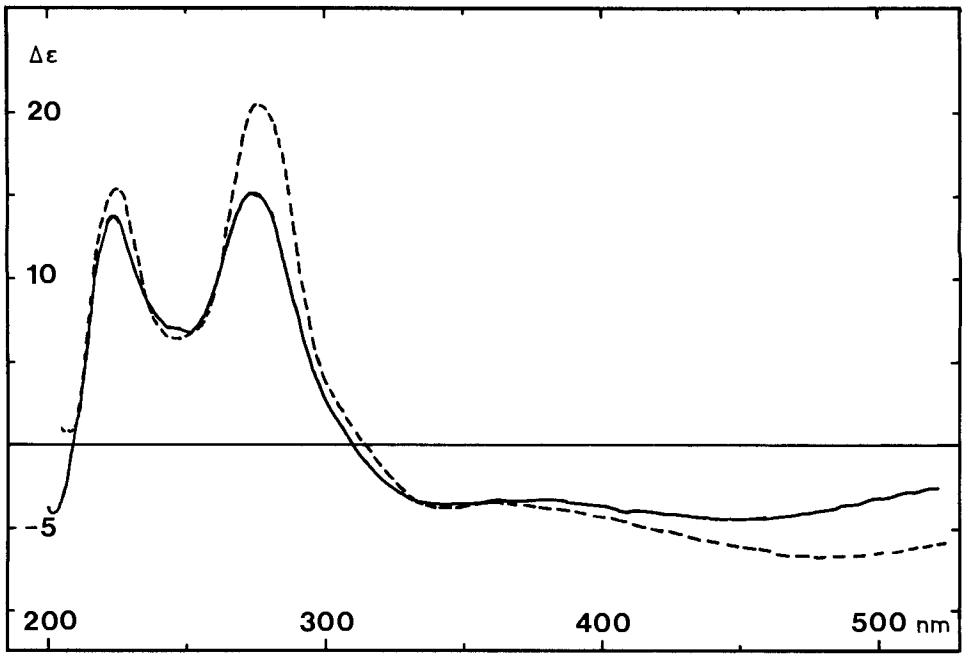


Fig. 4. *CD Spectrum of (−)-***23** *and (−)-***24** (dynamic 19:81 mixture) *in EPA* (Et_2O/pentane/EtOH 2:2:1) *at −10°* (——) *and after cooling to −180°* (----)

[20]) The DBS process of **21** and **22** as well as of **23** and **24** could be induced, in principle, also by light at −60° in $CDCl_3$ in the NMR spectrometer. However, already after short times of exposure to the light, new photoproducts of the same type were observed in both cases. Prolonged irradiation of **21**/**22** in *t*-BuOMe at room temperature yielded **9**/**12**. We will report later on these new photoreactions of *Stadler* compounds.

mol^{-1}. This corresponds to an average life time $\tau(298) = 1.8 \cdot 10^{-3}$ s of the individual forms (*i.e.* $(k_1 + k_{-1})_{298} = 5.5 \cdot 10^2\ s^{-1}$; *cf. Table 3, Exper. Part*)[21]).

That the DBS process in **23** and **24** occurs again with retention of the configuration of the heptalene skeleton could easily be demonstrated by the *Stadler* reaction of (−)-(*P*)-**20** [3] under carefully controlled conditions at −15 to 0°[22]). The resulting optically active mixture **23/24** showed the typical CD spectrum (in EPA) of a (*P*)-configurated heptalene skeleton at −10° (see *Fig. 4* and [3]). Since the DBS occurs rapidly at −10° in **23** and **24** ($(k_1 + k_{-1})_{263} = 37\ s^{-1}$) the observed (*P*)-configuration must be preserved in the course of the DBS process interconverting **23** and **24**.

3. Conclusion. – Our results clearly show that in the five-ring-annelated heptalenes, which are somewhat flatter than comparable five-ring-opened forms, the DBS' occur with retention of the configuration of the heptalene skeleton. The DBS process is energetically well separated from the process of racemization, which has to occur by double-ring inversion (DRI). The effect of substituents in the *'peri'*-positions (C(1), C(5), C(6), and C(10)) of the heptalenes on the DBS and DRI process is the same for both types of heptalenes, since it was found that $(k_1 + k_{-1})_{DBS}$ (**23/24**) > $(k_1 + k_{-1})_{DBS}$ (**21/22**) as well as k_{rac} (**3**/DBS isomer) > k_{rac} (**1a/2a**) (*cf.* [3]), *i.e.* the free C(6) position markedly reduces the E_a for the DRI as well as for the DBS process.

The rigid structure of the *Stadler* compounds clearly favors the DBS process in those cases where the steric hindrance in the *'peri'*-positions are comparable to that of the corresponding five-ring-opened heptalenes. Whereas the DBS isomers **1a** and **2a** are stable at room temperature, its *Stadler* counterparts **21** and **22**, respectively, are readily interconverted at this temperature. This effect can mainly be attributed to the fixed and directed C(3)=O group in **21** and **22**, in contrast to the (in principle) conformationally free C=O group of the $COOCH_3$ moiety at C(1) in **1a** and **2a**. As the C(3)=O moiety of **21** and **22**, for steric reasons, should be oriented similarly in the transition state as in the ground state, one can expect especially a difference in the ΔS^* values for the processes **21**⇄**22** and **1a**⇄**2a**. Unfortunately, we do not have the activation parameters for the isomerization **21**⇄**22**. However, the ΔS^* value of $-23 \pm 6\ JK^{-1}mol^{-1}$ for the comparable process **23**⇄**24** (*cf. Scheme 10*) is, indeed, smaller (*i.e.* more positive) than that for **1a**⇄**2a** which is of the order of $-40 \pm 8\ JK^{-1}mol^{-1}$ (*cf.* [2]).

If we compare the thermal behavior of the DBS isomers **11/13** with that of the isomeric **23/24** the effect of steric hindrance in the *'peri'*-position on the DBS becomes again clear. According to the ^{1}H-NMR observations, the DBS process **11**⇄**13** (sharp signals for both isomers at 30°) is markedly slower than for **23**⇄**24** (coalescence of the signals at *ca.* 25°) due to the fact that **11/13** are sp^3- and **23/24** are sp^2-hydridized at C(3).

Recently, *Nakajima* and coworkers [6] postulated on the basis of a D_{2h}-like transition state for the DBS in heptalenes that π-acceptor substituent in positions 1, 3, 5, 6, 8, and 10 or π-donor substituents in positions 2, 4, 7, and 9 should favour the DBS. Indeed, the non-bonding HOMO of the flat heptalene skeleton possesses large orbital coefficients at C(1), C(3), C(5), C(6), C(8), and C(10) and, correspondingly, the anti-bonding LUMO at

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[21]) The kinetic data should only be taken as approximate values, because the signals for H–C(11) showed small, not resolved H,H couplings, so that the real natural line-width of the signals is not known. However, our global ΔS^* for **23**⇄**24** is of the same order as that reported for **1a**⇄**2a** ($-40 \pm 8\ JK^{-1}mol^{-1}$) [2].

[22]) Raising the temperature above 10° for more than 1 h led to nearly complete racemization of **23** and **24**.

C(2), C(4), C(7), and C(9) (*cf.* [9]) which will favorably interact with the π-acceptor and π-donor substituents, respectively. These effects should stabilize the D_{2h} structure of the heptalene skeleton in the transition state and, thus, lower the transition-state energy. We cannot observe such an effect in our heptalene derivatives which are heavily substituted at the *'peri'*-positions and wherein the DBS process occurs at its best *via* a D_2-like transition state which is dominated by steric effects.

Inspection of the measured DBS equilibrium position of the heptalene derivatives shows that this equilibrium is well on the left side, *i.e.* on the side of the structures with C(1)=C(10a) bonds (*i.e.* C(1)=C(2) bonds in the five-ring-annelated structures) and C(2)=C(3) ($\triangleq$ C(6)=C(7)), as long as a C=O group is linked to C(2) ($\triangleq$ C(6)). The torsion angle between this C=O group and the s-*cis*-oriented C=C bond (C(2)=C(3) or C(6)=C(7)) amounts to 10–13° according to the X-ray structure analysis of several heptalene derivatives (*cf.* [1–4]) and thus indicates a good conjugative interaction between both π-systems. On the other hand, the X-ray structure analysis of 1,2-anhydride **5** indicates a strong torsional strain on the C(10a)=C(1) bond (*cf. Table 1*). Therefore, it seems quite reasonable that, in going from **11** to its isomeric structure **23** (or from **9** to **21**), the DBS equilibrium position is strongly shifted from the left to the right side, *i.e.* in favour of a double bond between C(2) and C(6) (see **24** (or **22**)). Obviously, the s-*trans*-conjugation of the C(3)=O group with the C(2)=C(6) bond is energetically more favorable than the corresponding s-*cis*-conjugation with the C(1)=C(2) bond in **23** (or **21**). This seems to be a general effect in heptalene derivatives with a π-acceptor substituent in a *'peri'*-position, because the heptalenedicarboxylate **4** (*cf. Fig. 1* and [4]) also strongly favours the DBS isomer with a C(4)=C(5) bond (comparable to the C(2)=C(6) bond in **22** or **24**) in the rapidly established thermal equilibrium at room temperature.

There is no doubt, that heptalene chemistry becomes now more and more predictable.

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Experimental Part

General. See [1] [3] [4]. Irradiations in NMR tubes (∅ 5 mm) were performed as follows: the soln. of the heptalene (*ca.* 5 mg) in $CDCl_3$ (0.3 ml) was freed from O_2 by introduction of Ar. Then, the soln. was cooled with dry ice/Et_2O and irradiated for 5 to 30 min with a Xe high-pressure lamp (1000 W) through a H_2O filter (10 cm) and glass condensing lenses. The UV part of the light was largely reduced by the glass lenses, however, light of 320 nm could partially pass. The following ^{1}H-NMR measurements at 360 MHz were performed at −50°, and after warming up to r.t. again at −50°.

1. Thermal and Light-Induced Isomerizations. – 1.1. rac-*5,6,8,10-Tetramethylheptalene-1,2-dicarboxylic Anhydride* (**6**) *and* rac-*1,6,8,10-Tetramethylheptalene-4,5-dicarboxylic Anhydride* (**7**). Anhydride **6** [3] in $CDCl_3$ was irradiated as described at −60°. ^{1}H-NMR at −50° (*Fig. 2*) indicated the formation of **7** (41.5%) as the only new product. ^{1}H-NMR ($CDCl_3$, −50°) of **7**: 1.68 (*s*, CH_3–C(1)); 1.78 (*s*, CH_3–C(6)); 1.98 (*d*, *J* (CH_3–C(10), H–C(9) = 1.4, CH_3–C(10)); 2.01 (*d*, *J*(CH_3–C(8),H–C(7)) = 1.2, CH_3–C(8)); 6.03 (*quint.*-like *s*, H–C(9)); 6.15 (br. *s*, H–C(7)); 6.66 (*d*, *J*(3,2) = 11.4, H–C(3)); 6.97 (*d*, *J*(2,3) = 11.4, H–C(2)). ^{1}H-NMR ($CDCl_3$, −50°) of **6** (58.5%): 1.82 (*s*, CH_3–C(6)); 2.07 (*d*, *J*(CH_3–C(8),H–C(9)) = 1.2, CH_3–C(8)); 2.11 (*dd*, *J*(CH_3–C(5),H–C(4))

= 1.45, J(CH$_3$–C(5),H–C(3)) ≈ 0.7, CH$_3$–C(5)); 2.27 (*d*, J(CH$_3$–C(10),H–C(9)) = 1.3, CH$_3$–C(10)); 6.30 (br. *s*, H–C(7)); 6.33 (*quint.*-like *s*, H–C(9)); 6.57 (*dq*, J(4,3) = 6.5, J(H–C(4),CH$_3$–C(5)) = 1.45, H–C(4)); 7.34 (*dq*, J(3,4) = 6.5, J(H–C(3),CH$_3$–C(5)) ≈ 0.7, H–C(3)).

Integration of the ^{1}H-NMR of **6** at *ca.* 30° indicated 2.2% of **7**. This composition was also obtained after warming up of the irradiated mixture of **6** (58.5%) and **7** (41.5%).

1.2. rac-*3,3-Dimethoxy-9,11,13,15-tetramethyl-4-oxatricyclo[8.5.0.0^{2,6}]pentadeca-1,6,8,10,12,14-hexaen-5-one*[4]) (**9**) *and* rac-*3,3-Dimethoxy-9,11,13,15-tetramethyl-4-oxatricyclo[8.5.0.0^{2,6}]pentadeca-2(6),7,9,11,13,15-hexaen-5-one*[4]) (**12**). 1.2.1. *Irradiation of* **9**. The *Stadler* compound **9** (0.200 g, 0.61 mmol) [3] was irradiated in *t*-BuOMe (250 ml) for 2 h at r.t. The solvent was evaporated and the residue separated on several TLC plates (silica gel, hexane/Et$_2$O 7:3) to yield **12** (0.094 g, 47%; R_f 0.42) as a yellow oil which crystallized in pale yellow plates after dissolution in Et$_2$O; m.p. 117–118°. As a second fraction of the TLC, **9** (0.080 g, 40%; R_f 0.36) was recovered.

12: UV (cyclohexane): λ_{max} 209 (4.33), 231 (sh, 4.17), 270 (4.28), 310 (sh, 3.56), *ca.* 380 (2.75, very br. tailing to longer λ); λ_{min} 247 (4.04), 358 (2.70). IR (KBr): 1773 (5-ring lactone). ^{1}H-NMR (270 MHz, CDCl$_3$): 1.767 (*s*, CH$_3$–C(9)); 1.807 (*s*, CH$_3$–C(15)); 2.000 (*s*, with f.s., CH$_3$–C(11), CH$_3$–C(13)); 3.294, 3.556 (2 *s*, 2 CH$_3$O); 6.023 (br. *s*, H–C(12)); 6.113 (br. *s*, H–C(14)); 6.623, 6.651 (*AB*, J(*AB*) = 11.5, H–C(7), H–C(8)); the positions of CH$_3$–C(9) and CH$_3$–C(15) as well as of H–C(12) and H–C(14) may be interchanged. MS: 326 (61, $M^{+\cdot}$), 311 (7), 295 (35, $M^{+\cdot}$–CH$_3$O$^\cdot$), 294 (65, $M^{+\cdot}$–CH$_3$OH), 286 (8), 279 (19), 267 (17), 254 (13), 235 (25), 221 (15), 208 (41), 207 (45), 193 (100), 178 (44), 165 (28), 152 (15). Anal. calc. for C$_{20}$H$_{22}$O$_4$ (326.39): C 73.60, H 6.79; found: C 73.68, H 6.86.

1.2.2. *Control Experiments.* Both **9** and **12** (11 mg, 0.034 mmol) were irradiated separately in *t*-BuOMe (250 ml) at 18–20° through a *Pyrex* filter (wall ∅ 1.5 mm) for 2 h. HPLC (*Lichrosorb* 5 µm, 50-cm column, hexane/AcOEt 9:1, UV detector at 269 nm) indicated in both cases the presence of 40.7% of **9** and 59.3% of **12**. No other products could be detected by HPLC.

Similarly, **9** (2.4 mg, 7.4 µmol) or **12** (1.9 mg, 5.8 µmol) in tetralin (0.25 and 0.2 ml, resp.) was heated in the dark at 100° for 4 h. HPLC as above revealed in both cases the presence of 94.0% of **9** and 6.0% of **12**. No other products could be detected by HPLC.

1.3. rac-*12-Isopropyl-3,3-dimethoxy-9,15-dimethyl-4-oxatricyclo[8.5.0.0^{2,6}]pentadeca-1,6,8,10,12,14-hexaen-5-one*[4]) (**11**) *and* rac-*12-Isopropyl-3,3-dimethoxy-9,15-dimethyl-4-oxatricyclo[8.5.0.0^{2,6}]pentadeca-2(6),7,9,11,13,15-hexaen-5-one*[4]) (**13**). To a soln. of 0.5 ml (0.47 g, 6.5 mmol) of DMF in dried MeCN (2 ml) at –20° was added within 10 min a soln. of oxalyl chloride (0.19 ml, 0.28 g, 2.2 mmol) in MeCN (2 ml). The white precipitate of the iminium salt was diluted with additional MeCN (2 ml), and the corresponding methyl hydrogen dicarboxylate **10** (0.65 g, 2.0 mmol) [3] was added. The iminium salt slowly dissolved and the temp. raised to 2°. The yellow-to-orange-coloured soln. was again cooled to –20°, and dried MeOH (0.25 ml/0.2 g, 5 mmol) in pyridine (0.50 ml/0.49 g, 6.2 mmol) was added within 5 min. The dark orange soln. was extracted several times with CH$_2$Cl$_2$ and the extracts washed with aq. KHCO$_3$ soln. and with H$_2$O. The raw product (0.92 g) was further purified by prep. TLC (Et$_2$O/hexane 1:1). The pure product (0.53 g) was crystallized from Et$_2$O/hexane to yield **11** (0.43 g, 63%) as yellow to orange crystals; m.p. 117–119°. UV (hexane): λ_{max} 249 (4.28), 264 (sh, 4.18), 385 (sh, 4.05, with extended tailing); λ_{min} 227 (4.14). IR (KBr): 1762 (5-ring lactone); 1373, 1361 ((CH$_3$)$_2$C). ^{1}H-NMR (270 MHz, CDCl$_3$): 1.032, 1.056 (2 *d*, J = 6.8, (C*H*$_3$)$_2$CH); 2.190 (*dd*, J(CH$_3$–C(9),H–C(8)) = 1.45, J(CH$_3$–C(9),H–C(7)) ≈ 0.7, CH$_3$–C(9)); 2.203 (*s* with f.s., CH$_3$–C(15)); 2.444 (*sept.*, J = 6.8, (CH$_3$)$_2$C*H*); 3.173, 3.463 (2 *s*, 2 CH$_3$O); 5.711 (br. *d*-like *s*, J(11,13) ≈ 1.2, H–C(11)); 6.131 (*quint.*-like *d*, J(13,14) = 6.5, J(13,11) ≈ J(CH$_3$–C(15),H–C(13)) ≈ 0.6, H–C(13)); 6.194 (*dq*, J(14,13) = 6.5, J(H–C(14),CH$_3$–C(15)) ≈ 1.4, H–C(14)); 6.311 (*dq*, J (8,7) = 6.5, J(H–C(8),CH$_3$–C(9)) ≈ 1.4, H–C(8)); 7.158 (*dq*-like, J (7,8) = 6.5, J(H–C(7),CH$_3$–C(9)) ≈ 0.7, H–C(7)). MS: 340 (93, $M^{+\cdot}$), 325 (13), 310 (16), 309 (75, $M^{+\cdot}$ – CH$_3$O$^\cdot$), 308 (100, $M^{+\cdot}$ – CH$_3$OH), 300 (8), 297 (9), 294 (6), 293 (18), 282 (6), 272 (17). Anal. calc. for C$_{21}$H$_{24}$O$_4$ (340.42): C 74.09, H 7.11; found: C 74.17, H 7.30.

The irradiation of **11** in CDCl at –60° yielded, after 2 min (10 min), a mixture of 64% (17%) of **11** and 36% (83%) of **13**. No further compound could be detected by ^{1}H-NMR.

13: ^{1}H-NMR (360 MHz, CDCl$_3$, –50°): 1.13, 1.16 (2 *d*, J = 6.8, (C*H*$_3$)$_2$CH); 1.76 (br. *s*, CH$_3$–C(9)); 1.84 (br. *s*, CH$_3$–C(15)); 3.31, 3.64 (2 *s*, 2 CH$_3$O); 5.60 (br. *s*, H–C(11)); 6.41 (*d*, J(13,14) = 11.9, H–C(13)); 6.47 (*dd*, J(14,13) = 11.9, J(not assigned) = 1.0, H–C(14)); 6.63 (*d*, J (8,7) = 11.4, H–C(8)); 6.73 (*d*, J (7,8) = 11.4, H–C(7)); 7.30 (*s*, C*H*Cl$_3$ as shift reference).

After warming up of the photo-solution, the nearly exclusive presence of **11** was recognized. However, careful inspection of several ^{1}H-NMR at *ca.* 30° revealed the consistency of the presence of 1.3 ± 0.3% of **13** beside **11**.

1.4. (PM,3RS,1′SR)-*3-Methoxy-9,11,13,15-tetramethyl-3-(1′-phenylethoxy)-4-oxatricyclo[8.5.0.0^{2,6}]pentadeca-1,6,8,10,12,14-hexaen-5-one*[4]) (**14A**) *and* (PM,3RS,1′SR)-*3-Methoxy-9,11,13,15-tetramethyl-3-(1′-phenylethoxy)-4-oxatricyclo[8.5.0.0^{2,6}]pentadeca-2(6),7,9,11,13,15-hexaen-5-one*[4]) (**15A**). 1.4.1. *Irradiation of* **14A**. A

soln. of **14A** (0.190 g, 0.46 mmol) [3] in *t*-BuOMe (250 ml) was irradiated at 18–20° for 2 h. The presence of **15A** was indicated by a new spot in the TLC (silica gel, hexane/Et_2O 7:3; R_f 0.38 as compared to R_f 0.35 for **14A**). Evaporation, dissolution of the residue in hexane/Et_2O, and crystallization yielded two types of crystals which, after filtration, were separated mechanically. Isomer **14A** formed orange to red crystals (28 mg, 15%) and **15A** a yellow to orange crystal powder (26 mg, 14%). The latter was recrystallized from Et_2O to yield pure **15A.** M.p. 132–134°; the melt solidified again above 134° and showed total melting at 172–174°. Prep. TLC of the mother liquor yielded a further crop of pure **15A** (22 mg, 12%). UV (cyclohexane): λ_{max} 208 (4.47), 232 (sh, 4.17), 270 (4.29), 309 (sh, 3.57), 384 (br. 2.79); λ_{min} 248 (4.06), 357 (2.73). IR (KBr): 1771 (5-ring lactone). ^{1}H-NMR (250 MHz, $CDCl_3$): 1.523 (*d*, J = 6.5, CH_3–C(1')); 1.764 (*s*, CH_3–C(9)); 1.908 (*s*, CH_3–C(15)); 2.017, 2.029 (2 *d*-like *s*, each $J \approx 1{,}1$ CH_3–C(11), CH_3–C(13)); 3.264 (*s*, CH_3O); 5.388 (*q*, J = 6.5, H–C(1')); 6.051, 6.134 (2 br. *s*, H–C(12), H–C(14)); 6.563, 6.626 (*AB*, $J(AB)$ = 11.4, H–C(7), H–C(8)); 7.3 (*m*, 5 arom. H); the positions for CH_3–C(9) and CH_3–C(15) may be interchanged. MS: 416 (37, $M^{+\cdot}$), 295 (16), 294 (37), 280 (24), 235 (16), 208 (30), 207 (28), 193 (58), 178 (28), 165 (20), 105 (100). Anal. calc. for $C_{27}H_{28}O_4$ (416.52): C 77.86, H 6.78; found: C 77.58, H 6.85.

1.4.2. *Control Experiments.* A soln. of **14A** (1 mg, 2.4 μmol) in *t*-BuOMe (5 ml) was irradiated with a UV lamp for TLC analysis (*Camag*) at 254 nm at a distance of 10 cm. TLC on silica gel under standardized conditions with hexane/Et_2O 7:3 showed that only **15A** (R_f 0.54) was formed in the presence of **14A** (R_f 0.48). The diastereoisomer **15B** (R_f 0.58; see *1.5.2*) could not be detected.

In a thermal experiment, **15A** (0.5 mg, 1.2 μmol) was heated in tetralin (0.06 ml) in the dark for 1 h at 100°. TLC as described indicated the nearly complete transformation (> 95%) of **15A** into **14A**. The diastereoisomer **14B** (R_f 0.52; see *1.5.2*) could not be detected.

1.4.3. *Irradiation of (–)-(*P,*3*R,*1'*S*)-***14A***. The optically active *Stadler* compound (15 mg, 0.036 mmol; $[\alpha]_D^{20} = -1433°$ ($c = 1.12 \cdot 10^{-3}$, acetone) [3]) was irradiated in *t*-BuOMe (250 ml) for 2 h. Usual workup yielded a yellow oil (8 mg, 53%) which consisted of 72% of starting material and 28% of *(–)-(*P,*3*R,*1'*S*)-***15A*** according to its ^{1}H-NMR. ORD (cyclohexane): 699 (–1435), 463 (–12609, T), 415 (0), 370 (18300, P), 343 (14400, T), 296 (109740, P), 277 (0). ^{1}H-NMR (250 MHz, $CDCl_3$): a weak *s* at 3.141 (CH_3O of **15B**) indicated the presence of *ca.* 2% of **15B**.

1.5. *(*PM,*3*RS,*1'*RS*)-3-Methoxy-9,11,13,15-tetramethyl-3-(1'-phenylethoxy)-4-oxatricyclo[8.5.0.0^{2,6}]pentadeca-1,6,8,10,12,14-hexaen-5-one*[4]) (**14B**) *and (*PM,*3*RS,*1'*RS*)-3-Methoxy-9,11,13,15-tetramethyl-3-(1'-phenylethoxy)-4-oxatricyclo[8.5.0.0^{2,6}]pentadeca-2(6),7,9,11,13,15-hexaen-5-one*[4]) (**15B**). 1.5.1. *Light-Induced Transformation of* **14B** *into* **15B**. Pure **14B** (R_f 0.52; [3]) was irradiated as described for **14A** (see *1.4.2*). The photolyzed soln. contained, according to the standardized TLC, only **15B** (R_f 0.58). Its diastereoisomer **15A** (R_f 0.54) could not be detected.

1.5.2. *Irradiation of (–)-(*P,*3*R,*1'*R*)-* **14B** (25 mg, 0.06 mmol; $[\alpha]_D^{20} = -1320°$ ($c = 1.01 \cdot 10^{-3}$, acetone) [3]) as described in *1.4.3* yielded a yellow oil (13 mg, 52%) consisting of 65% of starting material and 35% of (–)-(*P*,3*R*,1'*R*)-**15B** according to ^{1}H-NMR. ORD (cyclohexane): 699 (–1215), 463 (–11460, T), 417 (0), 365 (18660, P), 344 (13780, T), 297 (111830, P), 278 (0). ^{1}H-NMR (250 MHz, $CDCl_3$): 1.556 (*d*, J = 6.6, CH_3–C(1')); 1.754 (*s*, CH_3–C(9)); 1.884 (*s*, CH_3–C(15)); 1.941 (br. *s*, CH_3–C(11)); 1.986 (*d*-like *s*, $J \approx 1.1$, CH_3–C(13)); 3.138 (*s*, CH_3O); 5.397 (*q*, J = 6.7, H–C(1')); 5.973, 6.093 (2 br. *s*, H–C(12), H–C(14)); 6.644 (*AB*, just resolved, $J(AB) \approx 11.5$, H–C(7), H–C(8)); *ca.* 7.3 (*m*, 5 arom. H); the positions of CH_3–C(9) and CH_3–C(15) as well as those of CH_3–C(11) and CH_3–C(13) may be interchanged; a weak *s* at 3.272 (CH_3O of **15A**) indicated the presence of 1–2% of **15A**.

1.6. rac-*5,5-Dimethoxy-9,11,13,15-tetramethyl-4-oxatricyclo[8.5.0.0^{2,6}]pentadeca-1,6,8,10,12,14-hexaen-3-one*[4]) (**21**) *and* rac-*5,5-Dimethoxy-9,11,13,15-tetramethyl-4-oxatricyclo[8.5.0.0^{2,6}]pentadeca-2(6),7,9,11,13,15-hexaen-3-one*[4]) (**22**). 1.6.1. *2-Methyl 1-Hydrogen* rac-*5,6,8,10-Tetramethylheptalene-1,2-dicarboxylate* (**19**). Anhydride **6** (2.10 g, 7.5 mmol) was suspended in dried MeOH (50 ml) at 20° and treated with a freshly prepared soln. of Na (0.275 g, 12 mmol) in MeOH (80 ml). An immediate colour change from reddish brown to yellow indicated the opening of the cyclic anhydride (*cf.* [3]). The soln. was diluted with H_2O, acidified with 3N aq. HCl and extracted several times with Et_2O. The Et_2O extracts were washed with H_2O, dried, and evaporated: yellow powder (2.5 g, 107%) of a 4:1 mixture **19**/**8** (^{1}H-NMR). The mixture was used without further purification (see *1.6.2*). IR (KBr): 2542, 2526 (COOH); 1711, 1688 (COOR, COOH). ^{1}H-NMR (80 MHz): 1.78 (*s*, CH_3–C(6)); 1.93–2.16 (3*s*, CH_3–C(5), CH_3–C(8), CH_3–C(10)); 3.71 (*s*, CH_3OOC–C(1) of **8**; *ca.* 20%); 3.73 (*s*. CH_3OOC–C(2) of **19**; *ca.* 80%); 6.07 (br. *s*, H–C(9)); 6.22 (br. *s*, H–C(7)); 6.33 (*d* with f.s., J = 6, H–C(4)); 7.58 (*d* with f.s., J = 6.5, H–C(3) of **8**; *ca.* 20%); 7.70 (*d* with f.s., J = 6, H–C(3) of **19**; *ca.* 80%). MS: 312 (4, $M^{+\cdot}$), 280 (100, $M^{+\cdot} - CH_3OH$), all other signals identical with those of **6**.

1.6.2. *Mixture* **21**/**22**. To the suspension of the iminium salt (6.6 mmol, prepared according to *1.3* (*cf.* [3])) in MeCN (in total 17 ml), was added the crude **19** (1.88 g, *ca.* 6 mmol; see *1.6.1*) below 0°. The reaction started at 0° by dissolution of the iminium salt. The temp. was lowered again to −20°, and MeOH (0.75 ml, 0.6 g, 15 mmol) was added in pyridine (1.5 ml, 1.47 g, 18.6 mmol). After stirring for 50 min at −10° the red-orange mixture was extracted 3 times with CH_2Cl_2 and the extracts washed with aq. $KHCO_3$ soln. and H_2O. The residue (2.45 g, yellow-to-orange-coloured oil) of the CH_2Cl_2 extracts was further purified by prep. TLC (Et_2O/hexane 1:1) to yield 1.8 g (92%) of **21**/**22** which still contained *ca.* 20% of **9** (^{1}H-NMR). The by-product could be completely removed by fractionated crystallization (Et_2O/hexane). This procedure yielded pure isomer **22** (1.16 g, 59%) in uniform red needles. M.p. 120-121°. Dissolution of the red needles in $CDCl_3$ at r.t. yielded **21**/**22** 18:82 (^{1}H-NMR), whereas dissolution of the precooled red needles at −60° in $CDCl_3$ led only to **22** (^{1}H-NMR; see later). **22**: UV (hexane, r.t.): λ_{max} 228 (sh, 4.18), 240 (sh, 4.15), 273 (4.29), tailing from 305 to 400; λ_{min} 249 (4.12). IR (KBr, powdered crystals of **22**): 1766 (5-ring lactone). ^{1}H-NMR (360 MHz, $CDCl_3$, −60°): 1.715 (*s*, CH_3–C(15)); 1.812 (*s*, CH_3–C(9)); 1.971 (*d*-like *s*, $J(CH_3–C(11),H–C(12)) \approx 1.3$, CH_3–C(11)); 2.024 (*d*-like *s*, $J(CH_3–C(13),H–C(14)) \approx 1.2$, CH_3–C(13)); 3.457, 3.559 (2*s*, 2 CH_3O); 6.052 (br. *s*, H–C(12)); 6.168 (br. *s*, H–C(14)); 6.409 (*d*, $J(7,8) = 11.4$ H–C(7)); 6.910 (*d*, $J(8,7) = 11.4$, H–C(8)); 7.306 (*s*, $CHCl_3$ as shift reference). **21**/**22** (18:82): ^{1}H-NMR (400 MHz, $CDCl_3$, *ca.* 30°): signals of **21** (18%): 1.766 (*s*, CH_3–C(11)); 2.019, 2.023 (br. *d*-like signal, CH_3–C(9), CH_3–C(13)); 2.239 (*d*-like *s*, $J(CH_3–C(15),H–C(14)) \approx 1.2$, CH_3–C(15)); 3.297, 3.413 (2*s*, 2 CH_3O); 6.187 (br. *s*, H–C(12)); 6.206 (br. *s* with f.s., H–C(14)); 6.360 (*dq*-like, $J(8,7) \approx 6.5$, $J(H–C(8),CH_3–C(9)) \approx 1.3$, H–C(8)); 6.546 (*d* with f.s., $J(7,8) = 6.5$, H–C(7)); signals of **22** (82%): 1.695 (*s*, CH_3–C(15)); 1.773 (*s*, CH_3–C(9)); 1.954 (*d*-like *s*, $J(CH_3–C(11),H–C(12)) \approx 1.3$, CH_3–C(11)); 1.989 (*d*-like *s*, $J(CH_3–C(13)$, H–C(13)) ≈ 1.2, CH_3–C(13)); 3.420, 3.557 (2*s*, 2 CH_3O); 6.002 (br. *s* with f.s., H–C(12)); 6.116 (br. *s*, H–C(14)); 6.370 (*d*, $J(7,8) = 11.4$, H–C(7)); 6.795 (*d*, $J(8,7) = 11.4$, H–C(8)). ^{1}H-NOE (**21**): 2.02 (CH_3–C(13))→6.187 (H–C(12)), 8%, and 6.206 (H–C(14)), 8%; 2.239 (CH_3–C(15))→6.206 (H–C(14)), 7.9%. ^{1}H-NOE (**22**): 1.695 (CH_3–C(15))→6.116 (H–C(14)), 13%; 1.773 (CH_3–C(9))→1.954 (CH_3–C(11)), 1.4%, and 6.795 (H–C(8)), 11%; 1.954 (CH_3–C(11))→6.002 (H–C(12)), 10%; 1.989 (CH_3–C(13))→6.002 (H–C(12)), 10%, and 6.116 (H–C(14)), 11%. ^{1}H-NMR double resonances (**22**): 1.955 (CH_3–C(11))→6.002 (*d*-like *s*, $J(12,14) \approx 1.0$, H–C(12)). All H,H couplings in **22** have been corroborated by ^{1}H,^{1}H correlation NMR. MS: 326 (100, $M^{+\cdot}$), 311 (13, $M^{+\cdot} - CH_3^{\cdot}$), 295 (19, $M^{+\cdot} - CH_3O^{\cdot}$), 283 (5), 280 (6), 279 (10), 268 (9), 267 (46), 255 (7), 253 (8), 252 (32), 251 (45), 236 (58), 235 (79), 224 (7), 223 (13), 222 (5), 221 (10), 220 (12), 218 (6), 209 (15), 208 (41), 207 (46), 194 (15), 193 (15), 192 (37), 191 (27), 189 (17), 184 (13), 181 (10), 180 (5), 179 (21), 178 (38), 165 (46). Anal. calc. for $C_{20}H_{22}O_4$ (326.39): C 73.60, H 6.79; found: C 73.79, H 6.77.

Irradiation of a $CDCl_3$ soln. of pure **22** that was not purged by Ar at −60° for 10 min yielded 5.5% of **21**. After introduction of Ar and further irradiation, several new and not identified products were formed at −60° (^{1}H-NMR). Repetition of the irradiation (6 h) at 18–20° in *t*-BuOMe yielded 8.5% of **9** and 9.3% of **12**. Both isolated compounds had ^{1}H-NMR and IR identical with those of authentic material (see *1.2* and [3]). The mixed m.p. showed no depression.

1.7. rac-*12-Isopropyl-5,5-dimethoxy-9,15-dimethyl-4-oxatricyclo[8.5.0.0^{2,6}]pentadeca-1,6,8,10,12,14-hexaen-3-one*[4]) (**23**) *and* rac-*12-Isopropyl-5,5-dimethoxy-9,15-dimethyl-4-oxatricyclo[8.5.0.0^{2,6}]pentadeca-2(6),7,9,11,13,15-hexaen-3-one*[4]) (**24**). 1.7.1. *Synthesis.* To the suspension of the iminium salt (4.4 mmol; prepared according to *1.3* (*cf.* [3])) in MeCN (in total 12 ml) was added the methyl hydrogen dicarboxylate **20** (1.31 g, 4.0 mmol) [3] below 0°. The reaction started at 4°. After 20 min, the red-brown soln. was cooled again to −20° and MeOH (0.5 ml, 0.4 g, 10 mmol) in pyridine (1.0 ml, 0.98 g, 12.4 mmol) was added. The extraction with CH_2Cl_2 (3 times) yielded, after the usual workup, a brown oil (1.95 g) which was further purified by prep. TLC (Et_2O/hexane 1:1) and crystallization: dark brown needles (0.95 g, 70%) of **23**/**24**. M.p. 101–102°. Dissolution of the crystals in $CDCl_3$ at r.t. yielded **23**/**24** 17:83. UV (hexane, r.t.): λ_{max} 270 (4.32) with extended tailing from 305 to 390; λ_{min} 236 (4.10). IR (KBr, powered crystals): 1764 (5-ring lactone): 1378, 1365 ($(CH_3)_2C$). ^{1}H-NMR (400 MHz, $CDCl_3$, *ca.* 30°): all signals were broadened and showed coalescence (except *sept.* for $(CH_3)_2CH$), attributable to rapid exchange between **23** and **24**: 1.105 (br. *d* with f.s., $J \approx 7$, $(CH_3)_2CH$); 1.6–1.9 (br., CH_3–C(9), CH_3–C(15)); 2.49 (*sept.* $J \approx 7$, $(CH_3)_2CH$); 3.40, 3.44 (br. *s* and *s*, resp., 2 CH_3O); 5.45–5.65 (br., H–C(11)); 6.25–6.40 (several br. signals, H–C(7), H–C(13), H–C(14)); 6.65–6.80 (br., H–C(8)). ^{1}H-NMR (360 MHz, $CDCl_3$; crystals dissolved at r.t. and measured at −30°): signals of **23** (17%): 1.044, 1.079 (2*d*, $J = 7.2, 6.7$, $(CH_3)_2CH$); 2.163 (br. *s*, CH_3–C(15)); 2.302 (br. *s*, CH_3–C(9)); 2.509 (*sept.*, $J = 6.7$, $(CH_3)_2CH$); 3.318, 3.444 (2*s*, 2 CH_3O); 5.880 (br. *s*, H–C(11)); 6.238 (badly resolved *AB*, $J(A,B) \approx 5.4$ H–C(13), H–C(14)); 6.385 (*d*, $J(8,7) \approx 6.5$, H–C(8)); 6.468 (*d*, $J(7,8) \approx 6.6$, H–C(7)); signals of **24** (83%): 1.104, 1.130 (2*d*, $J = 6.82, 6.88$ $(CH_3)_2CH$); 1.684 (*s*, CH_3–C(15)); 1.737 (*d*, $J(CH_3–C(9),H–C(11)) = 0.56$, CH_3–C(9)); 2.509 (*sept.*, $J = 6.7$, $(CH_3)_2CH$); 3.448, 3.493 (2*s*, 2 CH_3O); 5.495 (br. *s*, H–C(11)); 6.300 (*d*, $J(7,8) = 11.36$, H–C(7)); 6.386 (*AB*, $J(A,B) \approx 12$, H–C(13), H–C(14)); 6.818 (*d*, $J(8,7) = 11.38$, H–C(8)). MS:

340 (100, $M^{+\cdot}$), 326 (12), 325 (48), 310 (12), 309 (27), 308 (7), 297 (23), 293 (10), 282 (18), 281 (58), 269 (7), 267 (12), 266 (9), 265 (14), 256 (18), 255 (89), 254 (8), 251 (13), 250 (7), 249 (10), 239 (8), 238 (6), 237 (6), 235 (8), 224 (6), 223 (14), 222 (15), 221 (50), 211 (8), 208 (10), 207 (27), 206 (12), 205 (11), 198 (7), 196 (12), 195 (15), 193 (10), 191 (23), 181 (8), 180 (13), 179 (40), 178 (27), 177 (9), 176 (9), 167 (15), 166 (12). Anal. calc. for $C_{21}H_{24}O_4$ (340.42): C 74.09, H 7.11; found: C 74.20, H 7.17.

Prolonged irradiation of **23**/**24** in $CDCl_3$ soln. at −60° under Ar yielded several new and not identified products (*cf. 1.6*).

1.7.2. *Thermodynamic and Kinetic Measurements.* The ^{1}H-NMR of a *ca.* 5% soln. of **23**/**24** in $CDCl_3$ was measured at different temp. (region of H–C(11) of both isomers, 5.5–5.9 ppm). *Table 2* shows the equilibrium constants K obtained from integration of the signals of H–C(11) of both isomers in the range of slow exchange (213–253 K). *Table 3* contains the τ values at different temp. (233–333 K) derived from a line-shape analysis in taking into account the temp. dependence of ΔG in the range of 213–253 K.

Table 2. *Temperature Dependence of the Equilibrium Constant* K *for the DBS Process* **23**⇄**24**

Temperature [K]	Composition [%]		K
	23	**24**	
213	15.7	84.3	5.371
223	16.6	83.4	5.035
233	17.1	82.9	4.878
243	17.7	82.3	4.673
253	18.0	82.0	4.558

Table 3. *Global Life Times* τ $(1/(k_1 + k_{-1}))$ *in the DBS Process* **23**⇄**24** *in Dependence of the Temperature*

Temperature [K]	τ [10^3 s]	Temperature [K]	τ [10^3 s]
233	558	293	2.21
243	200	298	1.82
253	94.5	303	1.51
263	27.0	313	0.609
273	12.1	323	0.314
283	5.06	333	0.156

1.7.3. *Mixture (−)-(*P*)-***23***/(−)-(*P*)-***24***.* To a soln. of the iminium salt (2.2 mmol; prepared according to *1.3* (*cf.* [3])) in MeCN (in total 6 ml) at −15° was added (−)-(*P*)-**20** (0.68 g, 2.1 mmol; $[\alpha]_D^{20} = -1725°$ ($c = 0.001$, acetone)) and the mixture stirred at −15°, until all of the iminium salt had been dissolved (red-brown soln.). After cooling to −25° MeOH (0.5 ml, 0.4 g, 12.4 mmol) in pyridine (0.5 ml, 0.48 g, 6.2 mmol) was added. After additional stirring for 25 min the dark brown soln. was diluted with H_2O and ice and extracted with ice-cooled CH_2Cl_2. The ice-cooled extracts were washed with cooled aq. $NaHCO_3$ soln. and ice/H_2O, dried, and evaporated at 0°. The resulting yellow oil was freed from residual CH_2Cl_2 at −25°/0.05 Torr. $[\alpha]_D^{20} = -1028°$ ($c = 1 \cdot 10^{-4}$, acetone). ORD (dioxane, 20°): 699 (−1962), 538 (−5114, T), 457 (0), 366 (11563, sh), 294 (48600, P), 275 (0), 264 (−14850, T), 256 (−2598, sh), 254 (0), 253 (4226, P), 251 (0), 246 (−14330, T), 241 (0), 236 (5500). After 2.5 h at 20°, all values were reduced by 2/3. CD (EPA, −10°; *cf. Fig. 4*)[23]): 550 (−5.74), 446.1 (14.79, max), 399.2 (−12.14, sh), 380.4 (−10.92, min), 346.1 (−12.10, max), 291 (24.96, sh), 274.9 (50.02, max), 251.3 (22.40, min), 245.5 (23.23, sh), 223.6 (45.59), 201.7 (−13.70). CD (EPA, −180°; *cf. Fig. 4*): 550 (−18.01), 524 (−19.69, sh), 502.5 (−21.68, sh), 473.4 (−22.22, max), 455.1 (−20.55, sh), 358.4 (−11.61, min), 346.2 (−12.71, max), 309.3 (3.99, sh), 276.3 (67.52, max), 251.7 (21.97, sh), 247.0 (20.92, min), 225.1 (50.74, max), 208.1 (2.48, min).

2. Acid-Catalyzed Isomerizations. – 2.1. *Reaction of 5-Methyl 4-Hydrogen 1,6,8,10-Tetramethylheptalene-4,5-dicarboxylate* (**16**) *with MeOH under* Stadler *Conditions.* To a suspension of the iminium salt (1.5 mmol, prepared according to *1.3* (*cf.* [3])) in MeCN (in total 5.5 ml) at −10 to 0° was added **16** (0.25 g, 0.8 mmol; see [1]; prepared by selective saponification of the diester **2a** [1] with KOH in aq. EtOH at 20° for 2.5 h (*cf.* [3]); m.p. 137–139° (dec.)).

[23]) As in our preceding publications on optically active heptalenes [1] [3], the CD data are presented in $\lambda[\theta/1000]$ ($\theta = 3300 \cdot \Delta\varepsilon$) [10].

After dissolution of the iminium salt at 0°, the soln. was cooled again to −20°, and MeOH (0.11 ml, 0.09 g, 2.8 mmol) in pyridine (0.11 ml, 0.10 g, 1.1 mmol) was added. The usual workup yielded exclusively **9** (0.16 g, 61%) which was identical with an authentic sample (IR, ^{1}H-NMR, R_f).

2.2. *Isomerization of* **12** *into* **9** *in HCl/MeOH.* A soln. of **12** (11 mg, 0.034 mmol) in MeOH (1 ml) and 0.0106M HCl/MeOH (0.65 ml, 6.9 µmol HCl) was stored in the dark at r.t. for 7 d. TLC (silica gel, hexane/Et_2O 7:3): nearly no **12** (R_f 0.42) left, mainly **9** (R_f 0.36) and smaller amounts of **1a** (R_f 0.19) and **2a** (R_f 0.28).

The experiment was repeated under exact the same conditions with HCl/CD_3OD instead of HCl/MeOH. The reaction time was reduced to 2 d. Usual workup and prep. TLC yielded 2.4 mg (*ca.* 18%) of [^{2}H]-**12**, 3.6 mg (*ca.* 27%) of [^{2}H]-**9**, 3.8 mg (*ca.* 28.5%) of [^{2}H]-**2a**, and 3.5 mg (*ca.* 26.5%) of [^{2}H]-**1a**[24]).

[^{2}H]-**12**: R_f 0.42. MS: 332 (38, [$^2H_6$]-$M^{+\cdot}$), 329 (3.3, [$^2H_3$]-$M^{+\cdot}$), 149 (100), *i.e.* 92% of [$^2H_6$]-**12** and 8% of [$^2H_3$]-**12**.

[^{2}H]-**9**: R_f 0.36. MS: 332 (28, [$^2H_6$]-$M^{+\cdot}$), 329 (2.5, [$^2H_3$]-$M^{+\cdot}$), 149 (100), *i.e.* 92% of [$^2H_6$]-**9** and 8% of [$^2H_3$]-**9**.

[^{2}H]-**2a**: R_f 0.28. MS: 332 (48, [$^2H_6$]-$M^{+\cdot}$), 329 (38, [$^2H_3$]-$M^{+\cdot}$), 184 (100), 149 (49), *i.e.* 56% of [$^2H_6$]-**2a** and 44% of [$^2H_3$]-**2a**.

[^{2}H]-**1a**: R_f 0.19. MS: 332 (55, [$^2H_6$]-$M^{+\cdot}$), 329 (19, [$^2H_3$]-$M^{+\cdot}$), 184 (83), 149 (100), *i.e.* 74% of [$^2H_6$]-**1a** and 26% of [$^2H_3$]-**1a**.

Further reduction of the reaction time to 3 h yielded 72% of [^{2}H]-**12**, 13% of [^{2}H]-**9**, 9% of [^{2}H]-**2a**, and traces of [^{2}H]-**1a** (not isolated; see *Scheme 9*).

[^{2}H]-**12**: ^{1}H-NMR (250 MHz, $CDCl_3$, 30°): all signals identical with those of authentic **12** except for a 20% reduction of the intensity at 3.294 and 3.566 (2*s*, 2 CH_3O; integration reference: *AB* at 6.623 and 6.651 (H–C(7) and H–C(8)) = 2.00 H), *i.e.* the average ^{2}H-content is 1.2 ^{2}H/molecule. MS: 332 (4, [$^2H_6$]-$M^{+\cdot}$), 326 (51, $M^{+\cdot}$), 193 (100), *i.e.* 5% of [$^2H_6$]-**12**, 34% of [$^2H_3$]-**12**, and 61% of **12**; this corresponds to an average ^{2}H-content of 1.3 ^{2}H/molecule in perfect agreement with the ^{1}H-NMR measurement.

[^{2}H]-**9**: MS: 332 (12, [$^2H_6$]-$M^{+\cdot}$), 329 (54, [$^2H_3$]-$M^{+\cdot}$), 326 (20, $M^{+\cdot}$), 193 (100), *i.e.* 14% of [$^2H_6$]-**9**, 63% of [$^2H_3$]-**9**, and 23% of **9**.

[^{2}H]-**2a**: MS: 332 (13, [$^2H_6$]-$M^{+\cdot}$), 329 (100, [$^2H_3$]-$M^{+\cdot}$), 326 (< 3, $M^{+\cdot}$), 184 (89), *i.e.* 12% of [$^2H_6$]-**2a** and 88% of [$^2H_3$]-**2a**.

2.3. *Control Experiments.* 2.3.1. *Parallel Treatment of* **9** *and* **12** *with HCl/CD_3OD.* A soln. of **9** or **12** (12 mg, 0.037 mmol) in CD_3OD (1.5 ml) and 0.005M HCl/CD_3OD (1 ml, *ca.* 5 µmol HCl) at r.t. was left in the dark for 3.5 h, and [^{2}H]-**9** and [^{2}H]-**12** were recovered in 79% and 65% yield, respectively. MS: 1.5% of [$^2H_6$]-**9**, 22% of [$^2H_3$]-**9**, and 76.5% of **9**; 1.7% of [$^2H_6$]-**12**, 21.2% of [$^2H_2$]-**12**, and 77.1% of **12**[25]).

2.3.2. *Treatment of* **1a** *with HCl/CD_3OD.* A soln. of 5 mg (0.015 mmol) of **1a** in CD_3OD (0.5 ml) and HCl/CD_3OD (1 ml, *ca.* 7 µmol) was left for 30 h at r.t. in the dark. The recovered **1a** showed no CH_3O/CD_3O exchange (MS).

2.3.3. *Treatment of* **9** *with HCl/CH_3OH.* As described in *2.2* for 8 d. TLC: mainly unchanged **9**, traces of **1a**, no **12** or **2a**.

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[24]) The total yield of recovered heptalenes amounted to 119%. Solvent residues could not completely be removed.

[25]) The difference to the 3 h experiment described under *2.2* is attributable to the lower concentration of HCl in these experiments.