Diels–Alder Reactions of Cycloalkenones. 6. 4-Alkyl-2-cyclohexenones as Dienophiles[1]

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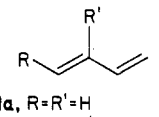
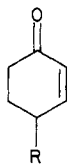
Diels–Alder reactions of 4-methyl-, 4-isopropyl- and 4-*tert*-butyl-2-cyclohexenones with 1,3-butadiene, isoprene, and (*E*)-piperylene under aluminum chloride catalysis are described. Structure analysis of the products and their hydrogenated derivatives by ^{13}C NMR spectroscopy is presented. The equilibria of the *cis*-octalones and *cis*-decalones with their trans epimers are interpreted in terms of conformational analysis. The syn–anti diene–dienophile interaction has been shown to be dependent on the nature of the diene and the size of the alkyl group of the dienophile.

As part of a general study of the acid-catalyzed Diels–Alder reaction the effect of a 5-alkyl substituent on the reactions of 2-cyclohexenones was inspected in depth recently.[1] In continuation of this investigation the effect of a 4-alkyl substituent was analyzed next, by the execution of Diels–Alder reactions of 1,3-butadiene (**1a**), isoprene (**1b**), and (*E*)-piperylene (**1c**) with 4-methyl- (**2a**),[3] 4-isopropyl- (**2b**)[3,4] and 4-*tert*-butyl-2-cyclohexenone (**2c**).[5]



1a, R=R'=H
b, R=H; R'=Me
c, R=Me; R'=H



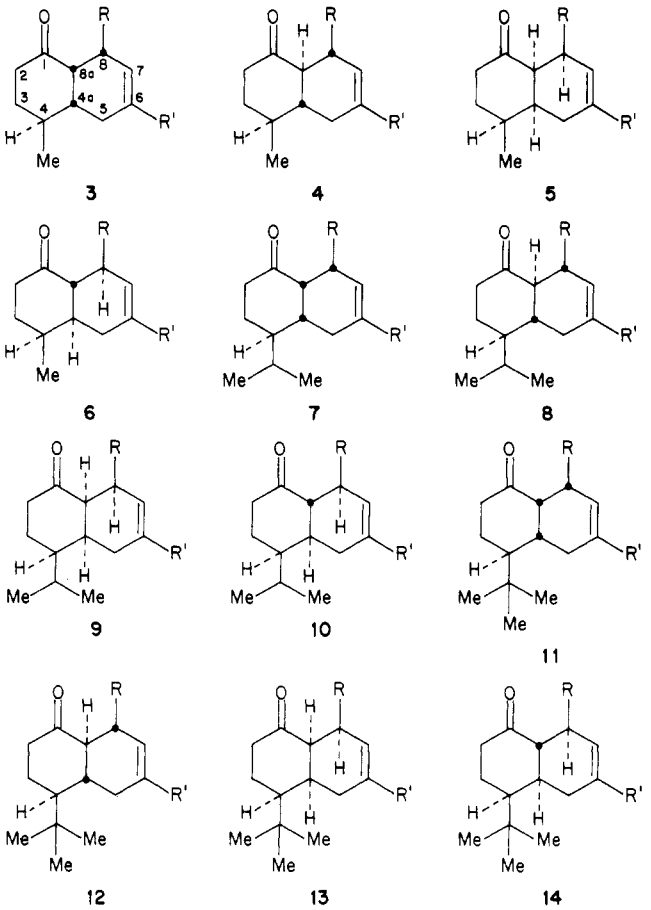
2a, R=Me
b, R=*i*-Pr
c, R=*t*-Bu

Reactions of the three dienes with the three dienophiles were carried out in all diene–dienophile combinations under aluminum chloride catalysis in toluene solution at 40–60 °C for 7–140 h and led generally to high yields of octalones, as shown in Table V. As in the case of the products of the reactions of the 5-alkyl-2-cyclohexenones,[1] the *cis*-octalones were kinetically based cycloaddition products[6] and in many instances underwent cis–trans isomerization under the reaction conditions. The piperylene-derived products revealed by the configuration of their allylic methyl group that they were endo Diels–Alder adducts.

Octalone and Decalone Configurations

The structures of the Diels–Alder adducts and their trans isomers were determined by ^{13}C NMR spectroscopy and their carbon shifts are listed in Tables II and III. In order to facilitate the shift assignment, some dihydro derivatives had to be prepared and their ^{13}C NMR spectra examined. The carbon shifts of the decalones (**15–24**) are listed on the formulas (Chart II).

Chart I[a]



3 **4** **5** **6** **7** **8** **9** **10** **11** **12** **13** **14**

[a] a, R = R' = H; b, R = H, R' = Me; c, R = Me, R' = H.

The structure of the *trans*-octalones **4a–c** is based on their strong carbon shift similarity with the unmethylated ketones analyzed earlier,[7] except for the methylated ring carbons and their immediate neighbors. The effect of the introduction of methyl groups on carbons 6 (**4b**) or 8 (**4c**) has been noted before[1,7] and the effect of C(4) methylation (**4a–c**) is that of the introduction of an equatorial, one-carbon substituent. The C(4)-methyl group is shielded ca. 4 ppm (compared to a sterically unfettered, equatorial methyl function on a rigidly held, chair-like cyclohexane

(1) For the previous paper, see: Angell, C.; Fringuelli, F.; Minuti, L.; Pizzo, F.; Porter, B.; Taticchi, A.; Wenkert, E. *J. Org. Chem.*, first in a series of three papers in this issue.

(2) (a) Università di Perugia. (b) University of California.

(3) Stork, G.; Brizzolara, A.; Landesman, H.; Szmuszkovicz, J.; Terrell, R. *J. Am. Chem. Soc.* **1963**, *85*, 207.

(4) For previous examples of the use of this ketone in Diels–Alder reactions, see: (a) Soffer, M. D.; Günay, G. E.; Korman, O.; Adams, M. B. *Tetrahedron Lett.* **1963**, 389. (b) Sakurai, H.; Osomi, A.; Saito, M.; Sasaki, K.; Iguchi, H.; Sasaki, J.-I.; Araki, Y. *Tetrahedron* **1983**, *39*, 883. (c) Fringuelli, F.; Pizzo, F.; Taticchi, A.; Ferreira, V. F.; Michelotti, E. L.; Porter, B.; Wenkert, E. *J. Org. Chem.* **1985**, *50*, 890.

(5) Garbisch, E. W., Jr. *J. Org. Chem.* **1965**, *30*, 2109.

(6) The constancy of the syn–anti product ratios with time at different temperatures is illustrated by the following examples. Monitored at various time intervals, the **1b–2a** reaction at 25 °C and 60 °C gave consistently the anti/syn values of 8 and 9, respectively, and the **1c–2b** reaction at 40 °C and 70 °C, 1.6 and 1.8, respectively.

(7) Fringuelli, F.; Pizzo, F.; Taticchi, A.; Halls, T. D. J.; Wenkert, E. *J. Org. Chem.* **1982**, *47*, 5056.

0022-3263/85/1950-4691$01.50/0

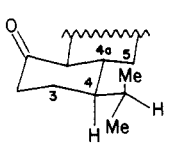
Table I. Aluminum Chloride Catalyzed Diels–Alder Reactions of Dienes 1 with Cyclohexenones 2

reactants	products	product ratios	% anti addition
1a–2a	**3a**,[a] **4a**, **5a**, **6a**	1:4:2.3:1.8	55
1a–2b	**7a**[a], **8a**, **9a**, **10a**[a]	3.5:30:15.5:1	67
1a–2c	**11a**, **12a**[a]	99:1	100
1b–2a	**3b**,[a] **4b**, **5b**,[b] **6b**[b]	3.3:26.7:2.3:1	90
1b–2b	**7b**,[a] **8b**,[c] **9b**[c]	1:90:9	91
1b–2c	**11b**, **12b**[a]	11.5:1	100
1c–2a	**3c**,[a] **4c**, **5c**, **6c**[a]	3.3:9:11.8:1	49
1c–2b	**7c**, **8c**, **9c**, **10c**[a]	37:24:38:1	61
1c–2c	**11c**, **12c**	9:1	100

[a] Not isolated in pure form, but identified by base-induced equilibration with its bridgehead epimer. [b] Not isolated in pure form (see ref 14). Reported in ref 4c.

ring), indicative of a γ-effect exerted by C(5) and reflected in the shift of the latter carbon site, albeit mildly. Ketone **6a** possesses an axial methyl group, as exemplified by the strong, shielding (γ-effects) of carbons, 2, 5, and 8a and by its own signal occupying an extraordinarily high-field position (over 10 ppm vis-à-vis that of an equatorial methyl group).

The C(4)-isopropylated ketones **8a–c** are *trans*-octalones with an equatorial isopropyl group, as indicated by shift comparisons with proper models as above. The δ values of the isopropyl carbons, C(3), C(4a), and C(5) reveal the preferred rotamer population of the isopropyl group to be that depicted in part structure **25**. The C(5) shift of ketones **8a–c** is reminiscent of that of the equatorially C-(4)-methylated compounds (**4a–c**) and the isopropyl methine is shielded strongly (over 5 ppm) as compared to one oriented equatorially in a cyclohexane without neighboring substituents.[1] This reciprocal γ-effect can be operative only in the absence of proximity of C(5) and an isopropyl methyl group. The resulting conformation **25**



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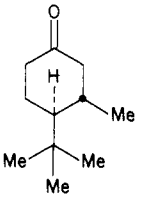

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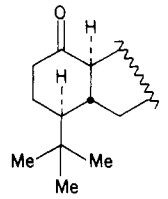

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foists upon the system γ-effects between C(3) and the isopropyl methyl group lying in the imaginary plane of the cyclohexane chair (reflected by ca. 5-ppm shielding of C-3 vs. the C-3 shift in the C-4 methylated compounds) as well as between the isopropyl methyl group perpendicular to the cyclohexane plane and C(3) (one more ca. 5-ppm shielding) and C(4a) (ca. 4-ppm shielding of this site vs.

Table II. ^{13}C Chemical Shifts of *trans*-Octalones[a]

	4a	4b	4c	6a	8a	8b	8c	12c
C(1)	211.8	211.9	211.9	212.3	211.8	212.2	212.2	213.8
C(2)	41.4	41.4	42.4	36.7	41.2	41.3	42.3	39.8
C(3)	35.0	35.0	36.2	33.1	24.5[c]	25.0[b]	26.0	24.6
C(4)	37.4	37.4	37.7	30.4	47.4	47.6	47.9	49.1
C(4a)	45.5	45.8	46.2	42.1	41.3	41.7	42.3	39.9
C(5)	31.6	36.5	31.1	29.5	30.8	35.9	30.4	35.8
C(6)	125.0[b]	131.9	123.1	125.3[b]	124.9[b]	132.0	123.1	124.3
C(7)	125.5[b]	119.6	132.5	125.5[b]	125.3[b]	119.6	132.5	132.8
C(8)	24.6	24.8	29.0	24.8	24.7[c]	24.7[b]	29.2	30.1
C(8a)	49.0	48.9	56.7	44.5	49.1	49.2	57.0	55.5
6-Me		23.1				23.2		
8-Me			21.0				21.1	20.7
4-Me	18.4	18.4	18.5	12.4				
i-Pr Me					14.7	14.8	14.8	
					21.5	21.6	21.7	
i-Pr CH					25.9	26.0	26.2	
t-Bu Me								29.1
t-Bu C								33.9

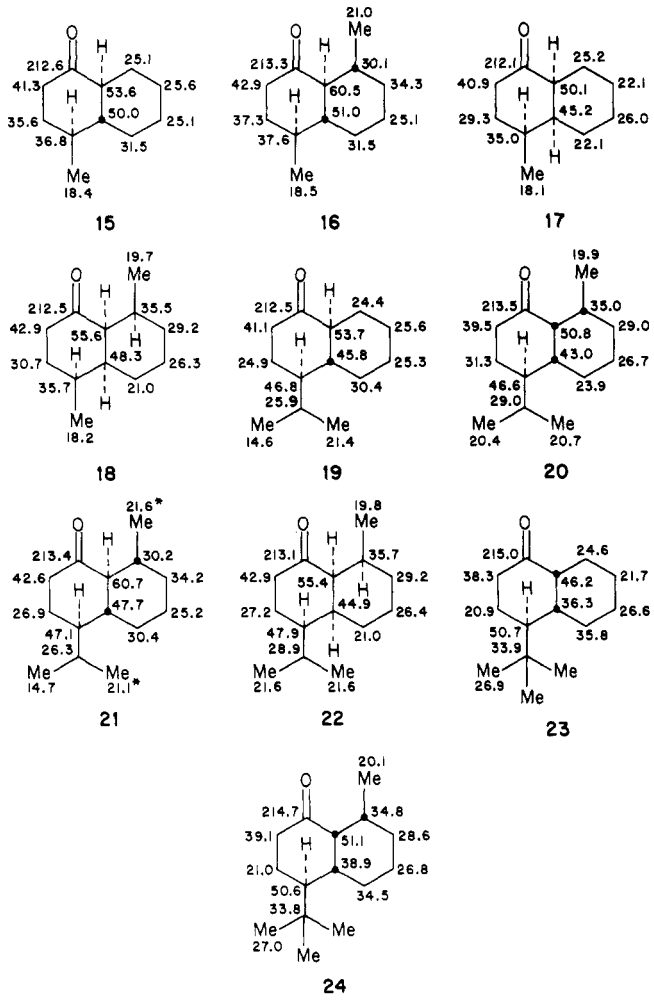
[a] The δ values are in parts per million downfield from Me_4Si; $\delta(Me_4Si) = \delta(CDCl_3) + 76.9$ ppm. [b,c] Signals in any vertical column may be interchanged.

Table III. ^{13}C Chemical Shifts of *cis*-Octalones[a]

	5a	5c	7c	9a	9b	9c	11a	11b	11c
C(1)	211.0	211.0	211.9	211.7	212.1	211.5	213.1	213.3	212.4
C(2)	40.3	42.2	39.0	40.3	40.5	42.1	36.8	37.0	37.5
C(3)	30.4	31.7	30.4	27.0	27.0	28.4	21.0	21.2	21.4
C(4)	34.6	35.2	45.3	46.9	46.8	47.4	49.7	49.8	50.0
C(4a)	40.9	44.6	39.6	37.6	38.1	41.3	31.7	32.2	35.1
C(5)	21.0	21.6	25.5	21.4	26.4	22.0	33.4	38.6	33.8
C(6)	124.1[b]	123.1	123.9	124.3[b]	131.3	123.3	125.4	132.2	123.7
C(7)	124.8[b]	131.3	131.4	124.9[b]	118.9	131.3	125.4	119.4	131.7
C(8)	23.6	32.6	32.5	23.8	23.9	32.8	23.0	23.2	32.4
C(8a)	48.3	54.1	49.2	48.2	47.9	53.8	44.1	43.7	49.1
6-Me					23.7			23.2	
8-Me		17.8[b]	18.0			17.7			18.1
4-Me	18.0	17.6[b]							
i-Pr Me			20.5	20.9	21.0	21.1			
			21.0	21.4	21.5	21.5			
i-Pr CH			29.1	28.9	29.0	28.9			
t-Bu Me							26.7	26.8	26.8
t-Bu C							33.7	33.8	33.6

[a] The δ values are in parts per million downfield from Me_4Si; $\delta(Me_4Si) = \delta(CDCl_3) + 76.9$ ppm. [b] Signals in any vertical column may be interchanged.

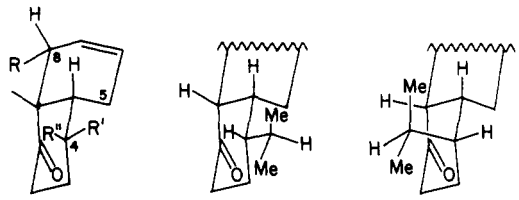
Chart II



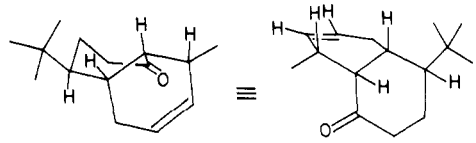
its shift in the C-4 methylated substances and ca. 5-ppm shielding of one of the isopropyl methyl groups).

The structure of *trans*-octalone **12c** is based on its being a bridgehead isomer of *cis*-octalone **11c** (vide infra), whose configuration has been settled by X-ray analysis (vide infra). Comparison of the shift data of **12c** and **8c** reveals general shift changes throughout the ring system too striking for a simple exchange of an isopropyl group by a *tert*-butyl function and strongly suggestive of a nonchair conformation of the ketonic ring as well as adulteration of the half-chair form of the olefinic ring. This unusual result, however, is interpretable as a consequence of the recent accumulation of conformational energy data on isopropyl- and *tert*-butylcyclohexanones structurally related to ketone **12c**. It has been noted[8] that, whereas 4-isopropyl-3-methylcyclohexanones in both cis and trans forms and *cis*-4-*tert*-butyl-3-methylcyclohexanone exist in chair conformations, the twist-boat form is favored by ca. 1 kcal/mol over the chair form for *trans*-4-*tert*-butyl-3-methylcyclohexanone (**26**), a structurally close relative of ketone **12c** (cf. part structure **27**). Hence the latter contains most likely a twist-boat ketonic ring.

The structure of *trans*-octalone **6a** having been assured and the ketone being epimerizable to *cis*-octalone **5a** makes the configuration of the latter secure. Furthermore, comparison of the carbon shifts of ketones **5a** and **5c** reveals the expected shift changes for the introduction of an equatorial C(8)-methyl group within conformation **28** for the bicycle.[1] The C(4)-methyl function being equatorial in this ring conformation is confirmed by the γ-effect exerted on it by C(5), as witnessed by the ca. 5-ppm shielding of both centers.[1] The C(4)-isopropylated ketones **9a–c** show the same shift behavior as the C(4)-methylated compounds **5a** and **5c**, thus being confined also to conformation **28**, and the spectral data are in accord with the isopropyl rotamer preference indicated in part structure **29**. The steric disposition of the isopropyl methine toward C(5) is the same as that of a C(4)-methylated ketone, thus causing little C(5) shift change (**5a** or **5c** vis-à-vis **9a** or **9c**, respectively), and the γ-effect expressing itself in the form of ca. 3-ppm shielding of the isopropyl methine (**9a–c** vs. C(3)-isopropylated *cis*-octalones).[1] Moreover, each of the isopropyl methyl groups exerts a γ-effect on ketonic ring carbons, one on C(3) and the other on C(4a), causing ca. 3-ppm shielding of these centers and yielding a shift equivalence to the methyl groups. The structure of the remaining C(4)-isopropylated ketone (**7c**) is based on its epimer relationship with *trans*-octalone **8c**, whose configuration has been determined (vide supra). Comparison of the δ values of cis ketone **7c** with those of its C(4) epimer **9c** and of equatorially C(3)-isopropylated *cis*-octalones[1] shows the compound to carry an axial isopropyl group within the same conformation (**28**) as that of *cis*-octalones **5** and **9**. The side chain prefers the orientation depicted in part structure **30**, as indicated by the removal of a γ-effect on C(5) (**7c** vs. **9c**) and the imposition of such an effect on C(2) as well as C(8a) (**7c** vs. **9c**).



The structure of **11c** derives from a single-crystal X-ray crystallographic analysis, which shows it to possess a ketone ring in slightly twisted boat form with an equatorial *tert*-butyl group and an olefinic ring in envelope form (in which carbons 4a, 5, 6, 7, and 8 lie in a plane) with an equatorial methyl function, i.e., conformation **31**. Shift



comparison among the *tert*-butylated ketones **11a–c** shows a conformational identity. Whereas the ketonic ring of the *cis*-octalones of type **28** is able to accommodate an axial C(4)-isopropyl group (**7c**, **30**), it refuses the imposition of an equally positioned *tert*-butyl group within the cyclohexanone chair, transforming instead into a more stable boat form. Despite the conformational difference of their ketonic rings compounds **7c** and **11c** show an amazing shift similarity at carbons 6, 7, 8, and 8a[9] and the C(8)-methyl group. This phenomenon is too striking to be a coincidence and hence suggests an identical conformation of the olefinic ring in the two substances, i.e., an envelope form. Furthermore, the shift integrity of the five carbons is

(8) Konopelski, J. P.; Sundararaman, P.; Barth, G.; Djerassi, C. *J. Am. Chem. Soc.* **1980**, *102*, 2737.

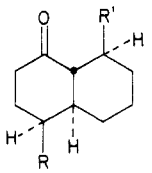
(9) The removal of the γ-effect of the axial isopropyl group on C(8a) in ketone **7c** must be compensated by a new one in **11c** due to the C(3)–C(8a) nonbonded interaction in the boat-like ring.[10]

maintained in compounds **5c** and **9c**, allowing for the removal of the γ-effect on C(8a) by the axial isopropyl group of ketone **7c**. If it be assumed that at least one of the contributing factors to the conformational disposition of the olefinic ring is the nonbonded repulsion of the carbonyl oxygen and the C(8)-methyl group, any change in the distance of the two centers from each other could affect, however subtly, the ring conformation. Inspection of the molecular models reveals a shorter distance between the peri substituents in a half-chair olefinic ring than in one of envelope form (both bicycles containing chair-like cyclohexanones as in **5c**, **7c**, and **9c**) and a similar relationship in the *cis*-octalone containing a boat-like ketonic ring (**11c**).

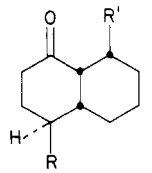
Except for the obvious cyclohexene–cyclohexane difference the decalones **15–24** possess the same conformations as their stereochemically related octalones.

The ^{1}H NMR spectra data, when interpretable (Experimental Section), are in accord with the above assignment of configuration. The two methyl groups of the isopropyl substituents of *cis*-octalones **7c** and **9a–c** and *cis*-decalones **20** and **22** exhibit identical or nearly the same hydrogen shifts (0.98 ± 0.03 ppm) and thus a similar chemical environment. This fact is consistent with conformation **29** for ketones **9a–c** and **22** and orientation **30** for compounds **7c** and **20**. The isopropyl methyl hydrogens of the *trans*-octalones **8a–c** and *trans*-decalones **19** and **21** resonate at markedly different field positions (0.76 ± 0.02 and 0.99 ± 0.02 ppm), in accord with their equatorial orientation. The unique methyl hydrogen shift (0.98 ± 0.02 ppm) of the *tert*-butyl groups of all *tert*-butylated ketones shows these compounds to possess equatorial *tert*-butyl functions (their axial counterparts being expected to resonance at ca. 1.12 ppm[11]).

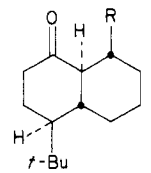
Even though the octalones **3a–c**, **6c**, **7a**, **7b**, **10a–c**, **12a**, and **12b** and the decalones **32–34** were not examined by



32a, R=Me; R'=H
b, R=R'=Me
c, R=*i*-Pr; R'=Me



33a, R=Me; R'=H
b, R=R'=Me
c, R=*i*-Pr; R'=H



34a, R=H
b, R=Me

spectroscopy as a consequence of their low availability, their structures are secure in view of their equilibrium relationship with their epimers.

Cis–Trans Equilibria

It was of interest to carry out cis–trans isomerizations of the 1-octalones and 1-decalones produced in the present study, in order in part to aid in their structure determination and to establish thermodynamic parameters of possible use in future work. Equilibria of the bridgehead epimers were established in ethanolic sodium ethoxide and the results are illustrated in Table IV.

In the C(4)-methyl and -isopropyl series of compounds the cis–trans equilibrium behavior of the decalones is similar to that of the octalones. In the case of the ketone pairs which restrict the C(4) substituent to an equatorial orientation (**3a–4a**, **3b–4b**, **33a–15**, **7a–8a**, **7b–8b**, **33c–19**) in the trans compound this epimer is favored at equilibrium, this tendency being enhanced by the equatorial

Table IV. Equilibrium Constants for the Cis–Trans Isomerism of Octalones and Decalones[a]

octalone pairs	K	octalone pairs	K	decalone pairs	K
3a–4a	79	**9b–10b**	0.01	**17–32a**	2
3b–4b	19	**9c–10c**	0.3	**18–32b**	6
3c–4c	≥200	**11a–12a**	0.1	**20–21**	53
5a–6a	0.7	**11b–12b**	0.1	**22–32c**	0.1
5c–6c	5	**11c–12c**	2	**23–34a**	0.1
7a–8a	16			**24–34b**	0.4
7b–8b	≥200			**33a–15**	49
7c–8c	19			**33b–16**	≥200
9a–10a	0.1			**33c–19**	12

[a] In ethanol at 22 °C, based on GC analysis. *K* is the trans-ketone/cis-ketone ratio.

C(8)-methyl group (**3c–4c**, **33b–16**, **7c–8c**, **20–21**). In situations in which the trans ketones hold an axial C(4) substituent the trend toward the trans epimer is decreased, making the C(4)-methylated ketones of nearly equal energy content (**5a–6a**, **17–32a**) and causing the C(4)-isopropylated ketones to be favored as cis epimers (**9a–10a**, **9b–10b**). Once again, the introduction of an equatorial C(8)-methyl group modifies the equilibrium in the trans epimer direction, thus making the axial C(4)-methyl compounds prefer the trans configuration (**5c–6c**, **18–32b**) and the axial C(4)-isopropyl compounds decrease their cis epimer preference (**9c–10c**, **22–32c**).

The C(4)-*tert*-butylated octalones (**11a–12a**, **11b–12b**) and decalones (**23–34a**) prefer a cis configuration, presumably because of greater nonbonded repulsion of the equatorial *tert*-butyl group (within twist-boat ketonic rings) and the equatorial C(5) hydrogen.[12] As in the case of the C(4)-isopropylated ketones, the presence of an equatorial C(8)-methyl function decreases the equilibrium displacement toward the cis epimer (**24–34b**). In accord with earlier observations[1] the presence of the C(6)–C(7) double bond displaces the equilibrium even further, creating a trans epimer preference (**11c–12c**).

Syn–Anti Diastereoisomerism

Inspection of Table I[14] reveals that the Diels–Alder reactions of 1,3-butadiene (**1a**) and (*E*)-piperylene (**1c**) show similar stereochemical behavior and are sensitive to the size of the alkyl group of the 4-alkyl-2-cyclohexenones **2**, the bulkier the side chain the more product of anti diene–dienophile interaction[15] being formed.[16] Contrastingly, the reactions of isoprene (**1b**) proceed by anti diene–dienophile interaction nearly independently of the size of the alkyl group.[17] The latter result cannot be ascribed

(10) Dalling, D. K.; Grant, D. M. *J. Am. Chem. Soc.* **1974**, *96*, 1827.
(11) Vierhapper, F. W.; Eliel, E. L. *J. Org. Chem.* **1979**, *44*, 1081.
(12) It is noteworthy that the cis–trans equilibrium of the bis-nor derivatives of the ketone isomer pair **23–34a** (containing cyclobutane units in place of the unsubstituted cyclohexane moieties) is displaced also toward the cis isomer,[13] although this equilibrium position may be the inherent property of the bicycles and not be dependent on the presence of a *tert*-butyl group.
(13) Cargill, R. L.; Morton, G. H.; Bordner, J. *J. Org. Chem.* **1980**, *45*, 3929.
(14) The minor products of the **1b–2a** reaction are bridgehead epimers of each other (their ratio changing with time during the course of the reaction until reaching a constant value) and are assigned structure **5b** and **6b** by analogy with the production of **5a** and **6a** as well as **5c** and **6c** in the **1a–2a** and **1c–2a** reactions, respectively.
(15) For a definition of the terms syn and anti in the context of the Diels–Alder reaction, see: ref 1.
(16) For comparison it is worth noting that the photochemically induced cycloadditions of enone **2b** with allene and enone **2c** with ethylene lead to 50% and 85% anti adducts, respectively.
(17) The Diels–Alder reaction between enone **2b** and isoprene trimethylsilylated on its methyl group under aluminum chloride catalysis has been reported recently[4b] to furnish in 56% yield a 19:1 mixture of the anti–cis adducts. In view of the present **1b–2b** cycloaddition data, showing the anti–trans octalone to be the predominant product and no regioisomer being formed, the earlier result is questionable.

Table V. Reaction Conditions of the Diels–Alder Reactions of Dienes 1 with Cyclohexenones 2[a]

reactants	diene/ketone[b]	$AlCl_3$/ketone[b]	ketone concn (M)	reactn temp (°C)	reactn time (h)	product yield (%)[c]
1a–2a	6	0.9	0.2	40	48	85
1a–2b	15	0.5	0.1	60	12	86
1a–2c	15	0.9	0.2	40	120	70
1b–2a	15	0.25	0.2	40	30	60
1b–2b[d]	15	0.25	0.1	60	7	75
1b–2c	15	0.5	0.1	40	140	40
1c–2a	3	0.25	0.2	40	16	85
1c–2b	3	0.5	0.1	40	27	93
1c–2c	9	0.5	0.1	40	75	83

[a] Complexation time, 40 min; complexation temperature, 22 °C.[7] [b] Ratio of equivalents. [c] GC-based yields. [d] From ref 4c.

to isoprene undergoing the sterically less demanding exo addition (piperylene showing only endo addition in the present cases), since such a process would be expected to yield products of both the syn and anti types and reactions between 2-cycloalkenones (structurally similar to **2**) and 1,3-dimethylbutadiene yield endo products.[18] A valid explanation for the syn–anti diastereoisomerism will have to await the accumulation of more data, but the heretofore generally accepted concept of Diels–Alder reactions occurring exclusively on the unalkylated side of the dienophile requires revision.[19]

Experimental Section

The experimental details of the Diels–Alder reactions and of the hydrogenation and base-induced equilibration of the products as well as the specifics on the spectral analyses of all octalones and decalones and on the instruments used are delineated in the Experimental Section of the adjoining publication.[1] The carbon shifts on formulas **15–24** are in ppm downfield from Me_4Si; $\delta(Me_4Si) = \delta(CDCl_3) + 76.9$ ppm. The asterisked shifts on formula **21** may be interchanged. The 2,4-dinitrophenylhydrazones were recrystallized in ethanol or ethanol–ethyl acetate.

Single-Crystal X-ray Crystallographic Analysis. One crystal of octalone **11c** was mounted on a Phillips PW 1100 automatic diffractometer, equipped with graphite-monochromatized Mo Kα radiation. The ketone was monoclinic and belonged to the space group $P2_1/n$ (from systematic extensions) with lattice parameters a = 16.571 (3) Å, b = 6.121 (3) Å, c = 13.617 (3) Å, and β = 100.91 (2)°. On the assumption of 4 molecules per unit cell the calculated density was 1.079 g/cm^3. The intensities of 1124 independent reflections were measured, 252 of which showed $I \leq 3\sigma(I)$ and thus were excluded from the subsequent computation. After the usual corrections the structure was solved by the direct multisolution method with the aid of the program SHELX.[20] Isotropic refinement by the least-squares method converged to an R value of 0.15. The structure work was terminated at this stage and showed the compound to possess structure **31** in the solid state.

Octalone 4a: mp 30–31 °C; IR 3035 (w, olefinic CH), 1718 (s, C=O), 1662 (w, C=C) cm^{-1}; ^{1}H NMR δ 1.02 (d, 3, J = 5 Hz, Me), 5.59 (m, 2, H-6, H-7). 2,4-Dinitrophenylhydrazone: mp 164–165 °C. Anal. Calcd for $C_{17}H_{20}O_4N_4$: C, 59.30; H, 5.85; N, 16.27. Found: C, 59.53; H, 5.73; N, 15.92.

Octalone 4b: mp 25–26 °C; IR 3040 (w, olefinic CH), 1720 (s, C=O), 1685 (w, C=C) cm^{-1}; ^{1}H NMR δ 1.03 (d, 3, J = 5 Hz, Me), 1.59 (s, 3, 6-Me), 5.31 (br s, 1, H-7). 2,4-Dinitrophenylhydrazone: mp 199–200 °C. Anal. Calcd for $C_{18}H_{22}O_4N_4$: C, 60.33; H, 6.19; N, 15.63. Found: C, 60.09; H, 6.03; N, 15.77.

Octalone 4c: mp 24–25 °C; IR 3025 (w, olefinic CH), 1718 (s, C=O), 1662 (w, C=C) cm^{-1}; ^{1}H NMR δ 0.94 (d, 3, J = 7 Hz, 8-Me), 1.00 (d, 3, J = 6 Hz, Me), 5.44 (m, 2, H-6, H-7). 2,4-Dinitrophenylhydrazone: mp 188–189 °C. Anal. Calcd for $C_{18}H_{22}O_4N_4$: C, 60.32; H, 6.19; N, 15.63. Found: C, 60.15; H, 5.92; N, 15.79.

Octalone 5a: mp 28–29 °C; IR 3035 (w, olefinic CH), 1722 (s, C=O), 1665 (w, C=C) cm^{-1}; ^{1}H NMR δ 1.03 (d, 3, J = 6 Hz, Me), 5.45 (m, 2, H-6, H-7). Anal. Calcd for $C_{11}H_{16}O$: C, 80.44; H, 9.81. Found: C, 80.36; H, 9.76.

Octalone 5c: IR 3030 (w, olefinic CH), 1725 (s, C=O), 1659 (w, C=C) cm^{-1}; ^{1}H NMR δ 1.00 (d, 3, J = 6 Hz, Me), 1.14 (d, 3, J = 7 Hz, 8-Me), 5.40 (m, 2, H-6, H-7). Anal. Calcd for $C_{12}H_{18}O$: C, 80.85; H, 10.17. Found: C, 80.45; H, 10.32.

Octalone 6a was isolated in small quantity, sufficient only for ^{13}C NMR spectral analysis (see Table II).

Octalone 7c: IR 3020 (w, olefinic CH), 1725 (s, C=O), 1660 (w, C=C), 1390, 1375 (m, $CHMe_2$) cm^{-1}; ^{1}H NMR δ 1.01 (d, 6, J = 6 Hz, Me_2), 1.20 (d, 3, J = 7 Hz, 8-Me), 5.48 (m, 2, H-6, H-7). Anal. Calcd for $C_{14}H_{22}O$: C, 81.50; H, 10.74. Found: C, 81.55; H, 10.75.

Octalone 8a: bp 82 °C (0.2 torr); IR 3020 (w, olefinic CH), 1720 (s, C=O), 1662 (w, C=C), 1390, 1373 (m, $CHMe_2$) cm^{-1}; ^{1}H NMR δ 0.79, 1.01 (d, 3 each, J = 6 Hz, Me_2), 5.63 (m, 2, H-6, H-7). 2,4-Dinitrophenylhydrazone: mp 189–190 °C. Anal. Calcd for $C_{19}H_{24}O_4N_4$: C, 61.26; H, 6.51; N, 15.05. Found: C, 61.58; H, 6.65, N, 14.71.

Octalone 8c: IR 3015 (w, olefinic CH), 1720 (s, C=O), 1665 (w, C=C), 1390, 1375 (m, $CHMe_2$) cm^{-1}; ^{1}H NMR δ 0.76, 0.99 (d, 3 each, J = 6 Hz, Me_2), 0.94 (d, 3, J = 7 Hz, 8-Me), 5.41 (m, 2, H-6, H-7). 2,4-Dinitrophenylhydrazone: mp 159–160 °C. Anal. Calcd for $C_{20}H_{26}O_4N_4$: C, 62.15; H, 6.79; N, 14.50, Found: C, 62.29; H, 6.85; N, 14.34.

Octalone 9a: bp 82 °C (0.2 torr); IR 3020 (w, olefinic CH), 1722 (s, C=O), 1665 (w, C=C), 1390, 1370 (m, $CHMe_2$) cm^{-1}; ^{1}H NMR δ 1.01 (d, 6, J = 5 Hz, Me_2), 5.46 (m, 2, H-6, H-7). 2,4-Dinitrophenylhydrazone: mp 186–187 °C. Anal. Calcd for $C_{19}H_{24}O_4N_4$: C, 61.26; H, 6.51; N, 15.05. Found: C, 60.98; H, 6.65; N, 14.81.

Octalone 9c: IR 3015 (w, olefinic CH), 1725 (s, C=O), 1660 (w, C=C), 1390, 1370 (m, $CHMe_2$) cm^{-1}; ^{1}H NMR δ 0.97, 1.01 (d, 3 each, J = 5 Hz, Me_2), 1.18 (d, 3, J = 7 Hz, 8-Me), 5.44 (m, 2, H-6, H-7). 2,4-Dinitrophenylhydrazone: mp 192–193 °C. Anal. Calcd for $C_{20}H_{26}O_4N_4$: C, 62.15; H, 6.79; N, 14.50. Found: C, 62.19; H, 6.58; N, 14.71.

Octalone 11a: mp 51–52 °C; IR 3020 (w, olefinic CH), 1725 (s, C=O), 1660 (w, C=C), 1395, 1365 (m, CMe_3) cm^{-1}; ^{1}H NMR δ 0.98 (s, 9, Me_3), 5.47 (br s, 2, H-6, H-7). Anal. Calcd for $C_{14}H_{22}O$: C, 81.50; H, 10.74. Found: C, 81.41; H, 10.81. 2,4-Dinitrophenylhydrazone: mp 150–151 °C. Anal. Calcd for $C_{20}H_{26}O_4N_4$: C, 62.15; H, 6.79; N, 14.50. Found: C, 61.82; H, 6.78; N, 14.24.

Octalone 11b: mp 41–42 °C; IR 3020 (w, olefinic CH), 1725 (s, C=O), 1680 (w, C=C), 1395, 1365 (m, CMe_3) cm^{-1}; ^{1}H NMR δ 0.98 (s, 9, Me_3), 1.58 (br s, 3, 6-Me), 5.26 (m, 1, H-7). Anal. Calcd for $C_{15}H_{24}O$: C, 81.76; H, 10.98. Found: C, 81.95; H, 11.04. 2,4-Dinitrophenylhydrazone: mp 177–178 °C. Anal. Calcd for $C_{21}H_{28}O_4N_4$: C, 62.99; H, 7.05; N, 13.99. Found: C, 62.64; H, 6.82; N, 13.77.

Octalone 11c: mp 33–34 °C; IR 3015 (w, olefinic CH), 1725 (s, C=O), 1655 (w, C=C), 1395, 1375 (m, CMe_3) cm^{-1}; ^{1}H NMR δ 0.98 (s, 9, Me_3), 1.26 (d, 3, J = 7 Hz, Me), 5.44 (br s, 2, H-6, H-7). Anal. Calcd for $C_{15}H_{24}O$: C, 81.76; H, 10.98. Found: C, 81.95; H, 11.06. 2,4-Dinitrophenylhydrazone: mp 165–166 °C. Anal. Calcd for $C_{21}H_{28}O_4N_4$: C, 62.97; H, 7.06; N, 13.99. Found: C, 62.87; H, 7.28; N, 13.45.

(18) Fringuelli, F.; Pizzo, F.; Taticchi, A.; Wenkert, E., unpublished observations.

(19) Whereas it was difficult to obtain comparison data on uncatalyzed, thermal Diels–Alder reactions with 2-cyclohexenones in view of the thermal instability of many of the products, one satisfactory reaction of this type, i.e., a **1c–2a** cycloaddition (155 °C, 60 h, 36% overall yield), afforded octalones **3c**, **4c**, **5c**, and **6c** in 4:2:1.3:1 ratio.

(20) Sheldrick, G. M. SHELX-76, a program for crystal structure determination, University of Cambridge, England, 1976.

Octalone 12c: IR 3020 (w, olefinic CH), 1718 (s, C=O), 1665 (w, C=C), 1399, 1368 (m, CMe_3) cm^{-1}; ^1H NMR δ 0.94 (s, 9, Me_3), 0.95 (d, 3, J = 6 Hz, 8-Me), 5.44 (br s, 2, H-6, H-7). Anal. Calcd for $C_{15}H_{24}O$: C, 81.76; H, 10.98. Found: C, 81.44; H, 10.93.

Decalone 15: IR 1714 (s, C=O) cm^{-1}; ^1H NMR δ 0.98 (d, 3, J = 5 Hz, Me). 2,4-Dinitrophenylhydrazone: mp 190–191 °C. Anal. Calcd for $C_{17}H_{22}O_4N_4$: C, 58.95; H, 6.40; N, 16.17. Found: C, 58.95; H, 6.14; N, 16.50.

Decalone 16: IR 1714 (s, C=O) cm^{-1}; ^1H NMR δ 0.91 (d, 3, J = 5 Hz, Me), 0.95 (d, 3, J = 6 Hz, Me). 2,4-Dinitrophenylhydrazone: mp 209–210 °C. Anal. Calcd for $C_{18}H_{24}O_4N_4$: C, 59.98; H, 6.71; N, 15.54. Found: C, 60.05; H, 6.62; N, 15.51.

Decalone 17: IR 1715 (s, C=O) cm^{-1}; ^1H NMR δ 1.02 (d, 3, J = 6 Hz, Me). Anal. Calcd for $C_{11}H_{18}O$: C, 79.46; H, 10.91. Found: C, 79.39; H, 10.82.

Decalone 18: IR 1717 (s, C=O) cm^{-1}; ^1H NMR δ 1.00 (d, 3, J = 6 Hz, Me), 1.10 (d, 3, J = 5 Hz, Me). Anal. Calcd for $C_{12}H_{20}O$: C, 79.94; H, 11.18. Found: C, 79.83; H, 11.28.

Decalone 19: IR 1722 (s, C=O), 1385, 1370 (m, $CHMe_2$) cm^{-1}; ^1H NMR δ 0.76, 0.99 (d, 3 each, J = 6 Hz, Me_2). 2,4-Dinitrophenylhydrazone: mp 207–208 °C. Anal. Calcd for $C_{19}H_{26}O_4N_4$: C, 60.93; H, 7.01; N, 14.96. Found: C, 61.21; H, 7.27; N, 14.70.

Decalone 20: IR 1710 (s, C=O), 1385, 1370 (m, $CHMe_2$) cm^{-1}; ^1H NMR δ 0.97, 1.00 (d, 3 each, J = 6 Hz, Me_2), 1.10 (d, 3, J = 7 Hz, 8-Me). Anal. Calcd for $C_{14}H_{24}O$: C, 80.71; H, 11.61. Found: C, 80.58; H, 11.60.

Decalone 21: IR 1713 (s, C=O), 1389, 1370 (m, $CHMe_2$) cm^{-1}; ^1H NMR δ 0.74, 0.97 (d, 3 each, J = 6 Hz, Me_2), 0.88 (d, 3, J = 7 Hz, 8-Me). 2,4-Dinitrophenylhydrazone: mp 157–158 °C. Anal. Calcd for $C_{20}H_{28}O_4N_4$: C, 61.84; H, 7.26; N, 14.42. Found: C, 61.50; H, 7.16; N, 14.11.

Decalone 22: IR 1713 (s, C=O), 1385, 1369 (m, $CHMe_2$) cm^{-1}; ^1H NMR δ 0.95 (d, 6, J = 5 Hz, Me_2), 1.07 (d, 3, J = 7 Hz, 8-Me). Anal. Calcd for $C_{14}H_{24}O$: C, 80.71, H, 11.61. Found: C, 80.95; H, 11.59.

Decalone 23: IR 1715 (s, C=O), 1395, 1369 (m, CMe_3) cm^{-1}; ^1H NMR δ 1.00 (s, 9, Me_3). Anal. Calcd for $C_{14}H_{24}O$: C, 80.71; H, 11.61. Found: C, 80.86; H, 11.63.

Decalone 24: mp 42–43 °C; IR 1716 (s, C=O), 1396, 1370 (m, CMe_3) cm^{-1}; ^1H NMR δ 1.00 (s, 9, Me_3), 1.13 (d, 3, J = 6 Hz, 8-Me). Anal. Calcd for $C_{15}H_{26}O$: C, 81.02; H, 11.78. Found: C, 81.13; H, 11.68.

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Diels–Alder Reactions of Cycloalkenones. 7. Reactions of Carvone[1]

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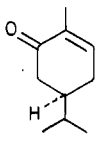
Diels–Alder reactions of (–)-carvone with 1,3-butadiene, isoprene, (*E*)-piperylene, and 1,3-dimethyl-1,3-butadiene under aluminum chloride catalysis are reported. Structure analysis of the products and some of their hydrogenated derivatives by ^{13}C NMR spectroscopy is described.

Recent, exhaustive studies of the acid-catalyzed Diels–Alder reaction of 4-[1] and 5-alkyl-2-cyclohexenones[3] with 1,3-butadiene and its 1- and 2-methyl derivatives have furnished a variety of octalones and decalones of potentially wide use. Thus, for example, the *tert*-butylated bicyclic ketones can be exploited in the area of conformational analysis and the methylated and isopropylated compounds in the field of terpene synthesis.[4] It now became of interest to investigate reactions of carvone (**1**) with dienes, not only for the rapid construction of sesquiterpenic ring skeleta containing an angular methyl group but also for gaining flexible entry into the realm of optically active substances in view of the ready availability of the monoterpene in (+) and (–) forms. As a consequence (–)-carvone (**1**) was submitted to Diels–Alder reactions with 1,3-butadiene (**2a**), isoprene (**2b**), (*E*)-piperylene (**2c**), and 1,3-dimethyl-1,3-butadiene (**2d**) under aluminum chloride catalysis.[5]



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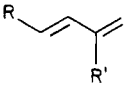

2a, R=R'=H
b, R=H; R'=Me
c, R=Me; R'=H
d, R=R'=Me

The reactions were carried out in toluene solution at 25–40 °C for 13–93 h and gave 80–88% yields of *cis*-octalones, as shown in Table I. The structures of the ketonic products were determined by ^{13}C NMR spectroscopy and the carbon shifts are listed in Table II.[7]

By comparison of the carbon shifts of angularly unmethylated *cis*-octalones and *cis*-decalones containing C(3)-isopropyl groups oriented cis to H(4a)[3] with ketones **3c,d** and **7**, respectively, it is possible to deduce the structures of the three new ketones as depicted by their

(1) For part 6, see: Angell, E. C.; Fringuelli, F.; Halls, T. D. J.; Pizzo, F.; Porter, B.; Taticchi, A.; Tourris, A. P.; Wenkert, E. *J. Org. Chem.*, second in a series of three paper in this issue.

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(3) Angell, E. C.; Fringuelli, F.; Minuti, L.; Pizzo, F.; Porter, B.; Taticchi, A.; Wenkert, E. *J. Org. Chem.*, first in a series of three papers in this issue.

(4) Fringuelli, F.; Pizzo, F.; Taticchi, A.; Ferreira, V. F.; Michelotti, E. L.; Porter B.; Wenkert, E. *J. Org. Chem.* **1985**, *50*, 890.

(5) For previous reactions of carvone with dienes, see (a) Nerdel, F.; Dahl, H. *Liebigs Ann. Chem.* **1967**, *710*, 90. (b) Harayama, T.; Cho, H.; Inubushi, Y. *Tetrahedron Lett.* **1975**, 2693; *Chem. Pharm. Bull. Jpn.* **1977**, *25*, 2273.

(6) Fringuelli, F.; Pizzo, F.; Taticchi, A.; Halls, T. D. J.; Wenkert, E. *J. Org. Chem.* **1982**, *47*, 5056.

(7) On the basis of the present data the δ values of the two methyl groups in ketone **9f** as well as **25d** of ref 6 require reversal.

0022-3263/85/1950-4696$01.50/0