Diels–Alder Reactions of Cycloalkenones. 5. 5-Alkyl-2-cyclohexenones as Dienophiles[1]

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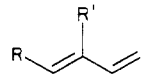
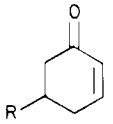
The Diels–Alder reactions of 5-methyl-, 5-isopropyl- and 5-*tert*-butyl-2-cyclohexenone with 1,3-butadiene, isoprene, and (*E*)-piperylene under aluminum chloride catalysis are described. Structure analysis of the adducts and some of their hydrogenation products mostly by NMR spectroscopy is presented. Base-induced isomerization of the octalones and decalones and conformational analysis of the equilibrants have been performed. The syn–anti diastereoisomerism of the cycloadditions has been inspected.

In connection with the continuing study of the acid-catalyzed Diels–Alder reaction of cycloalkenones[1] it became of interest to investigate the universality of the generally accepted concept of the exclusivity of diene–dienophile interaction on the unalkylated side of the dienophile in cases such as 5-alkylated or 5,6-dialkylated 2-cyclohexenones.[3] For this purpose it seemed necessary to acquire comparison data for reactions whose (a) product yields and (b) product material balances are high, on substituted 2-cyclohexenones, whose alkyl side chains (c) vary in size and (d) are located on carbons 4, 5, or 6. It could be anticipated that a possible consequence of such a study would be the acquisition of some insight into the heretofore unexplored conformational state of the dienophile during the course of the cycloaddition process. The present report is devoted to the Diels–Alder reactions of 1,3-butadiene (**1a**), isoprene (**1b**), and (*E*)-piperylene (**1c**) with 5-methyl- (**2a**),[4] 5-isopropyl- (**2b**)[5] and 5-*tert*-butyl-2-cyclohexenone (**2c**).[6]



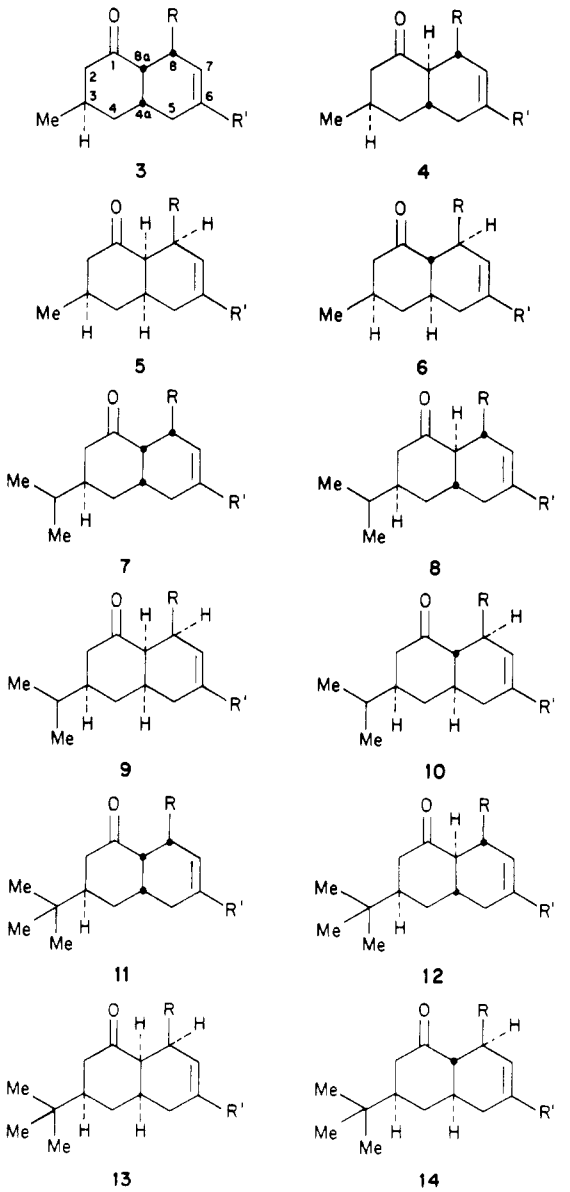
1a, R = R' = H
b, R = H; R' = Me
c, R = Me; R' = H



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

Reactions of the three dienes with the three dienophiles were executed in all diene–dienophile combinations under aluminum chloride catalysis in toluene solution at 22–70 °C for 2–44 h and led to 72–97% yields of octalones, as shown in Table V. As observed in earlier examples of reactions of C(2)-unsubstituted 2-cyclohexenones,[7] some of the primary products underwent cis-trans isomerization under the reaction conditions and the piperylene-derived products showed by the stereochemistry of their allylic methyl group that they were endo Diels–Alder adducts. The *cis*-octalones were kinetically based cycloaddition products, as shown by the constancy of the ratios of the products of different diene–dienophile approach throughout the course of the reactions at various temperatures.

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.

(1) For the previous paper, see: Fringuelli, F.; Pizzo, F.; Taticchi, A.; Ferreira, V. F.; Michelotti, E. L.; Porter, B.; Wenkert, E. *J. Org. Chem.* **1985**, *50*, 890.
(2) (a) Università di Perugia. (b) University of California.
(3) (a) Harayama, T.; Cho, H.; Ohtani, M.; Inubushi, Y. *Chem. Pharm. Bull. Jpn.* **1974**, *22*, 2784. (b) Oppolzer, W.; Petrzilka, M. *J. Am. Chem. Soc.* **1976**, *98*, 6722. (c) Harayama, T.; Cho, H.; Inubushi, Y. *Ibid.* **1977**, *25*, 2273. (d) Oppolzer, W.; Petrzilka, M. *Helv. Chim. Acta* **1978**, *61*, 2755. (e) Trost, B. M.; Caldwell, C. G.; Murayama, E.; Heissler, D. *J. Org. Chem.* **1983**, *48*, 3252.
(4) Crossley, A. W.; Renouf, N. *J. Chem. Soc.* **1915**, *107*, 602. Gannon, W. F.; House, H. O. *Org. Synth.* **1960**, *40*, 14, 41.
(5) Frank, R. L.; Hall, H. K., Jr. *J. Am. Chem. Soc.* **1950**, *72*, 1645.
(6) Chamberlain, P.; Whitham, G. H. *J. Chem. Soc., Perkin Trans. 2* **1972**, 130.
(7) (a) Fringuelli, F.; Pizzo, F.; Taticchi, A.; Halls, T. D. J.; Wenkert, E. *J. Org. Chem.* **1982**, *47*, 5056. (b) Fringuelli, F.; Minuti, L.; Pizzo, F.; Taticchi, A.; Halls, T. D. J.; Wenkert, E. *Ibid.* **1983**, *48*, 1810. (c) Fringuelli, F.; Pizzo, F.; Taticchi, A.; Wenkert, E. *Ibid.* **1983**, *48*, 2802.

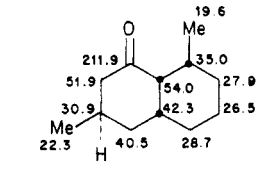
0022-3263/85/1950-4686$01.50/0

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

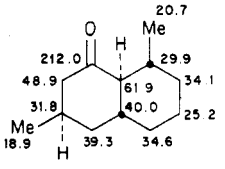
reactants	products	product ratios	% anti addition
1a–2a[a,b]	**3a, 4a**	1:4	96
1a–2b	**7a, 8a, 9a**,[c] **10a**	120:64:1:15	92
1a–2c	**11a, 12a, 14a**	24:8.3:1	97
1b–2a[b]	**3b, 4b**	2:1	97
1b–2b[b]	**7b, 8b**	6.6:1	92
1b–2c	**11b, 12b**,[c] **14b**	8.9:1.2:1	91
1c–2a	**3c, 4c, 6c**[d]	22.7:1.2:1	96
1c–2b[e]	**7c, 8c**	200:1	98
1c–2c[b]	**11c, 12c**	20.5:1	97

[a] Reaction described in ref 7a. [b] Two unisolated products account for 4%, 3%, 8%, and 3% of the mixtures of the reactions of **1a–2a**, **1b–2a**, **1b–2b**, and **1c–2c**, respectively. [c] Not isolated in pure form, but identified by base-induced equilibration with its bridgehead epimer. [d] A trace of its *cis*-octalone epimer (i.e., **5c**) was observed. [e] One unisolated product accounts for 2% of the product mixture.

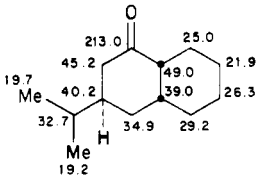
Chart II



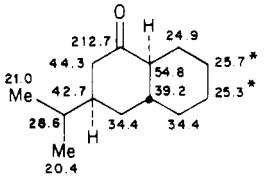
15
(dihydro-**3c**)



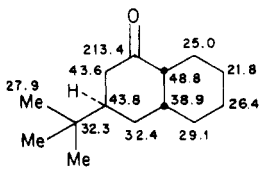
16
(dihydro-**4c**)



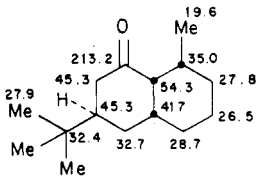
17
(dihydro-**7a**)



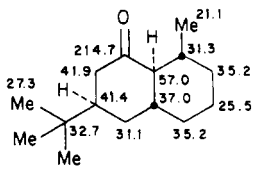
18
(dihydro-**8a**)



19
(dihyro-**11a**)



20
(dihyro-**11c**)



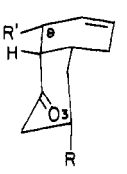
21
(dihydro-**12c**)

Octalone and Decalone Configurations

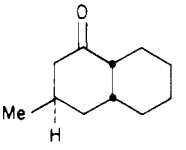
The structures of the Diels–Alder adducts and their trans isomers were determined by ^{13}C NMR spectroscopy, the carbon shifts of the octalones being listed in Tables II and III. For unambiguity of shift assignment the ^{13}C NMR spectra of some dihydro derivatives had to be inspected. The carbon shifts of the decalones **15–21**[8] are exhibited on their formulas (Chart II).

(8) The shifts of carbons 6 and 7 (numbering system as on ketone **3**) of the trans bicyclic ketones **24a**, **24c**, **26a**, **26b**, and **28a** of ref 7a require revision. The two δ values of each compound are to be exchanged and denoted as being interchangeable, showing the uniform bias toward a lower C(6) value as in *trans*-decalone **18** of the present report.

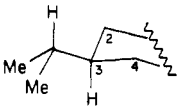
Comparison of the carbon shifts of structurally related ketones yields great insight into the configurations and conformations of the individual compounds. Thus, for example, the cis and trans isomers of the butadiene- and isoprene-based octalones can be differentiated from each other by the cis ketones exhibiting shielding of all their diene-derived ring carbons, as a shift comparison of the **3a–4a**, **3b–4b**, **7a–8a**, **7b–8b**, and **11a–12a** ketone pairs reveals. A similar differentiation of C(8a) epimers of the piperylene-based octalones (e.g., **3c–4c**, **7c–8c**, and **11c–12c**) is limited to the C(5), C(6), and C(7) shifts, the C(8) shift not being diagnostic in view of dissimilarities of the nonbonded interactions of the C(8) methyl group with the carbonyl oxygen affecting the δ value of C(8) of the epimers differently. Furthermore, it is noteworthy that in contrast to the minimal shielding of C(6), C(7), and C(8) of *cis*-octalones **3a**, **3b**, **7a**, **7b**, and **11a** (as well as of C(6) and C(7) of ketones **3c**, **7c**, and **11c**) carbon 5 is shielded dramatically in all these cis bicycles, indicative of γ-shifts exerted on C(5) by C(1) and C(3) and thus limiting the cis isomers to conformation **22**. The latter conformation appears to be the consequence of the C(3) and C(8) substituents of the *cis*-octalones (as well as the *cis*-decalones **15**, **17**, **19**, and **20**), assuming equatorial orientations therein. Comparison of the C(2) and C(4) shifts of C(3)-methylated vs. C(3)-isopropylated *cis*-octalones (**3a**, **3b**, and **3c** vs. **7a**, **7b**, and **7c**, respectively) and *cis*-decalones (**23**[7a] vs. **17**) reveals nearly identical $\Delta\delta$ values for the two ring carbons flanking C(3), showing the major rotamer population of the isopropyl group to be that depicted in part formula **24**.



22

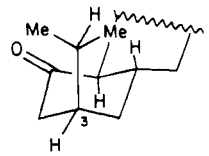


23

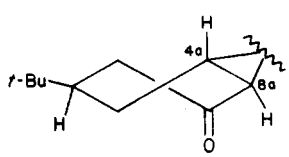


24

The group of *trans*-octalones includes four substances (**6c**, **10a**, **14a**, and **14b**) whose C(3)-alkyl groups are oriented equatorially toward a chair-like, six-membered ring, as indicated by the similarity of the $\Delta\delta$ values for C(2), C(3), and C(4) of these compounds and C(3)-unsubstituted models.[7a] The remaining C(3)-methylated and -isopropylated *trans*-octalones (**4a–c** and **8a–c**) possess axially disposed C(3)-alkyl groups, as shown most effectively by the reciprocal γ-effects, i.e., the shielding of C(4a) and the C(3)-methyl group of ketones **4a–c** vs. ketone **6c** and the shielding of C(4a) and the isopropyl methine in bicycles **8a–c** vs. *trans*-octalone **10a**. The same conclusion can be reached for *trans*-decalone **18**, since C(4a) is shielded, vis-à-vis, this carbon in *trans*-1-decalone[7a] and its isopropyl methine shows a signal upfield of that of ketones **8a–c**. From the vantage points of these results and conformational analysis the isopropyl group of compounds **8a–c** and **18** shows the rotamer population preference denoted in part formula **25**.



25



26

The remaining ketones, the *tert*-butylated *trans*-octalones **12a** and **12c** and *trans*-decalone **21**, reveal *tert*-butyl methyl shifts indistinguishable from any of all other

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

	4a[b]	4b	4c	6c	10a	8a	8b	8c	12a	12c	14a	14b
C(1)	211.7	212.1	211.3	211.3	212.3	211.9	212.4	211.8	215.2	214.5	212.8	212.2
C(2)	47.5	48.0	48.8	50.9	45.2	44.7	44.9	45.6	41.0	42.0	43.6	43.6
C(3)	30.3	30.8	31.5	34.4	44.2	42.9	43.0	43.8	41.4	42.0	48.1	48.1
C(4)	37.7	38.2[c]	38.6	41.7	36.1	34.6	34.7	35.0	30.8	30.3	33.9	33.9
C(4a)	34.3	34.9	35.4	39.3	38.7	34.9	35.3	35.7	33.0	33.8	38.7	39.0
C(5)	33.0	38.3[c]	33.0	32.9	33.4	33.6	38.6	33.3	34.4	34.1	33.5	38.4
C(6)	124.9[c]	132.4	123.5	123.3	125.2[c]	125.4[c]	132.6	123.7	126.0	124.5	125.3[c]	132.4
C(7)	125.3[c]	119.8	132.9	132.9	125.8[c]	125.9[c]	119.9	133.1	126.0	133.5	125.8[c]	119.8
C(8)	23.8	24.4	28.9	29.0	24.4	24.4	24.7	29.3	25.7	30.9	24.5	24.6
C(8a)	49.7	50.2	58.1	57.1	49.7	50.3	50.4	58.2	47.5	54.9	49.8	49.7
6-Me		23.1					23.2					23.2
8-Me			20.8	20.9				20.9[c]		20.6		
3-Me	18.4	18.6	18.6	22.3								
i-Pr Me					19.3	20.9	21.1	21.1[c]				
					19.1	20.4	20.5	20.5				
i-Pr CH					32.5	28.3	28.4	28.1				
t-Bu Me									27.4	27.3	27.1	27.1
t-Bu C									32.8	32.6	32.6	32.6

[a] The δ values are in parts per million downfield from Me_4Si; $\delta(Me_4Si) = \delta(CDCl_3) + 76.9$ ppm. [b] From ref 7a. [c] Signals in any vertical column may be interchanged.

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

	3a[b]	3b	3c	7a	7b	7c	11a	11b	11c
C(1)	210.5	212.3	210.6	211.6	211.9	211.0	212.1	212.3	211.5
C(2)	49.3	49.5	51.3	44.7	44.8	46.5	43.0	43.1	44.8
C(3)	30.7	30.6	32.1	41.4	41.4	42.9	45.1	45.0	46.6
C(4)	38.4	38.4	38.8	33.5	33.4	33.7	30.9	30.8	31.1
C(4a)	34.9	35.4	38.5	34.7	35.2	38.1	34.6	35.0	37.9
C(5)	26.7	31.7	26.6	26.4	31.5	26.7	26.4	31.4	26.7
C(6)	124.4[c]	131.7	123.5	124.5[c]	131.6	123.5	124.6[c]	131.7	123.8
C(7)	124.5[c]	118.4	130.8	124.7[c]	118.4	130.8	124.8[c]	118.5	131.0
C(8)	23.3	23.6	32.1	23.4	23.5	32.2	23.4	23.6	32.3
C(8a)	47.0	46.7	52.6	47.3	46.9	53.0	47.3	46.8	53.1
6-Me		23.2			23.5			23.6	
8-Me			17.4			17.5			17.6
3-Me	22.3	22.4	22.1						
i-Pr Me				19.7	19.7	19.6			
				19.2	19.3	19.3			
i-Pr CH				32.8	32.8	32.8			
t-Bu Me							27.1	27.1	27.2
t-Bu C							32.5	32.5	32.6

[a] The δ values are in parts per million downfield from Me_4Si; $\delta(Me_4Si) = \delta(CDCl_3) + 76.9$ ppm. [b] From ref 7a. [c] Signals in any vertical column may be interchanged.

tert-butylated ketones and hence characteristic of equatorial *tert*-butyl groups. All cyclohexanone carbons of the three compounds possess anomalous shifts, ruling out the presence of cyclohexane chair conformations. The overall shielding of the saturated ring carbons of the ketonic ring (especially of the site of attachment of the *tert*-butyl group) of octalone **12a**, contrasted with octalone **14a**, is in accord with the *tert*-butylated ring existing in twist boat form,[9] i.e., as in **26**. Direct proof of the configurations of the three bicycles emanates from the fact of their being formed on base-induced epimerization of their cis isomers (**11a**, **11c**, and **20**, respectively) (vide infra), compounds with established structures.

The ^1H NMR spectral data, when interpretable (Experimental Section), are in agreement with the above assignments of configuration. Thus, for example, the methyl hydrogen shifts of the isopropyl group of bicyclic ketones containing this side chain show a distinct dependency on conformation. Part structure **24**, offering a similar environment to the two methyl groups, is reflected by the identity of the methyl hydrogen shifts and by the invariance throughout the series of compounds incorporating an equatorial isopropyl group (0.92 ± 0.01 ppm for cis ketones **7a–c** and **17** and 0.95 ppm for trans ketone **10a**). The dissimilarity of the methyl hydrogen shifts (0.90 ± 0.01 and 0.95 ± 0.02 ppm) of substances with axial isopropyl groups (trans ketones **8a–c** and **18**) is in accord with part structure **25** in which the anisotropy of the carbonyl group affects the two methyl groups differently. The *tert*-butyl hydrogens of all *tert*-butylated bicycles (**11a–c**, **12a**, **12c**, **14a,b** and **19–21**) resonate at 0.90 ± 0.02 ppm, appreciably upfield of the characteristic ca. 1.05-ppm signal of axial *tert*-butyl groups[10] and thus indicative of the presence of an equatorial *tert*-butyl function in all the compounds containing this bulky side chain.

Whereas the structures of octalones **5c**, **9a**, **12b**, **13a**, **13b**, and **27** were not defined by spectroscopic means in view of the paucity of material, their configurations are established by their equilibrium relationship with epimers **6c**, **10a**, **11b**, **14a**, **14b**, and **19**, respectively (vide infra).

Cis–Trans Equilibria

With a large number of 1-octalones and 1-decalones in hand it seemed useful to investigate their stabilities with respect to cis–trans isomerization, in order to acquire a body of thermodynamic data of possible use in future work.

(9) Loomes, D. J.; Robinson, M. J. T. *Tetrahedron* **1977**, *33*, 1149. Huffman, J. W.; Mathews, F. J.; Balke, W. H. *J. Org. Chem.* **1984**, *49*, 4943.

(10) Eliel, E. L.; Koeber, Sr. M. C. *J. Am. Chem. Soc.* **1968**, *90*, 3444.

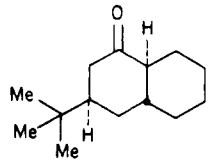
Table IV. Equilibrium Constants for the Cis–Trans Isomerism of Octalones and Decalones[a]

octalone pairs	K	octalone pairs	K	decalone pairs	K
3a–4a	4	**9a–10a**	77	**15–16**	10
3b–4b	3.5	**11a–12a**	0.5	**17–18**	1.3
3c–4c	19	**11b–12b**	0.3	**19–27**	0.3
7a–8a	1.9	**11c–12c**	4.6	**20–21**	0.7
7b–8b	1.8	**13a–14a**	99		
7c–8c	19	**13b–14b**	99		

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

Equilibria of the bridgehead epimers were established in ethanolic sodium ethoxide and the results are portrayed in Table IV.[11]

Inspection of the equilibrium data for the C(3)-methylated compounds reveals the trans ketones with an axial C(3)-methyl function (**28**) to be more stable than the



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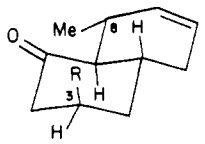

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cis isomers with an equatorial methyl group (**22**) and introduction of either an equatorial C(8) methyl group or a $\Delta^{6(7)}$ linkage to enhance the stability of the trans bicycles. These results are repeated in the C(3)-isopropylated series of ketones, albeit the trans/cis ratios being reduced, as expected from the conformational energy difference of methyl and isopropyl groups. In the case of the trans ketone containing an equatorial isopropyl function (**10a**) the trans bicycle is favored greatly. This effect is duplicated (to an even greater extent) by the trans ketones containing an equatorial *tert*-butyl group (**14a** and **14b**).[12] On the other hand, the C(3)-*tert*-butylated ketones, whose trans isomers require distortion of their ketonic ring into a twist-boat form (**26**) to accommodate an equatorial *tert*-butyl group (**12a,b**, **21**, and **27**), favor the cis isomer (conformation **22**).[13] The only exception to this trend is the **11c–12c** equilibrium position, favoring the trans isomer. Hence, once again, the introduction of an equatorial C(8) methyl group into the ring system enhances the stability of the trans ketone.[14,15] Inspection of molecular models shows that the repulsive, nonbonded interaction of the equatorial C(8) methyl group with the carbonyl oxygen, i.e., a peri effect, diminishes from *cis*-octalones (**22**) and *cis*-decalones to their trans isomers containing either chair (**28**) or twist-boat (**26**) ketonic ring conformations.

(11) Whereas the **5c–6c** equilibrium was established, it is not included in Table IV in view of the availability of only small quantities of ketones.

(12) For analogous examples, see: (a) Gream, G. E.; Laffer, M. H.; Serelis, A. K. *Aust. J. Chem.* **1978**, *31*, 803. (b) House, H. O.; Umen, M. J. *J. Org. Chem.* **1972**, *37*, 2841.

(13) For analogous examples, see: (a) Reference 12a. (b) House, H. O.; Phillips, W. V. *J. Org. Chem.* **1978**, *43*, 3851. (c) House, H. O.; Phillips, W. V.; VanDerveer, D. *Ibid.* **1979**, *44*, 2400.

(14) Comparison of the equilibrium data of the **11a–12a** and **11c–12c** ketone pairs with the **19–27** and **20–21** pairs, respectively, shows the equatorial C(8)-methyl effect to be expressed in both decalones and octalones, albeit more strongly in the latter.

(15) The preference of a *trans*-octalone (**12c**) containing a twist-boat ring over a *cis*-octalone (**11c**) with two equatorial side chains appears, at first glance, to be surprising. However, the energy difference between an equatorially *tert*-butylated cyclohexane chair and twist-boat within a decalin system being only ca. 2 kcal/mol[13b,c] and being lowered by the introduction of a carbonyl group[16] permits a displacement of the equilibrium toward the trans isomer.

(16) Allinger, N. L.; Tribble, M. T.; Miller, M. A. *Tetrahedron* **1972**, *28*, 1173.

Syn–Anti Diastereoisomerism

As inspection of Table I indicates,[17] the Diels–Alder reactions proceed preponderantly, albeit not exclusively, by anti[18] diene–dienophile interaction independently of size of dienophile substituent and diene structure. The uncatalyzed, thermal Diels–Alder reaction between (*E*)-piperylene (**1c**) and 5-methyl-2-cyclohexenone (**2a**) (155 °C, 36 h, 32% overall yield) produced octalones **3c**, **4c**, and **6c** in 17:1:3 ratio, thus showing a lower anti selectivity than the acid-catalyzed Diels–Alder reaction.[19] The strong preference for anti cycloaddition is a function of the acid catalysis and the position of the dienophile substituent. As a consequence it is premature to extend the results of the present study to reactions of 2-cyclohexenones with side chains in other positions.

Experimental Section

Melting points were determined on a Büchi 510 melting point apparatus and are uncorrected. Infrared spectra of carbon tetrachloride solutions were recorded on a Perkin-Elmer 257 spectrophotometer. ^{1}H NMR spectra were observed on carbon tetrachloride solutions, containing Me_4Si as internal standard (δ = 0 ppm), on JEOL JNM-60 HI and Varian EM-390 spectrometers. The ^{13}C NMR spectra of $CDCl_3$ solutions were taken on a Nicolet NT-200, wide-bore, broad-band spectrometer, operating with an Oxford magnet at 50.31 MHz in the Fourier transform mode. The carbon shifts on formulas **15–21** are in ppm downfield from Me_4Si [$\delta(Me_4Si) = \delta(CDCl_3) + 76.9$ ppm] and the asterisked shifts on formula **18** may be interchanged. GC analyses were performed on Carlo Erba HRGC-5160 and Hewlett-Packard 5880 A chromatographs with 50-m (0.2 mm diameter) Carbowax 20M capillary columns and an "on-column" injection system (internal standards: *p*-methoxy- and *p*-chloroacetophenone). Absorption chromatography was carried out on 230-mesh Merck silica gel or 4:1 silica gel–silver nitrate columns (elution with pentane–ether gradients). All solid Diels–Alder adducts were crystallized from pentane and the 2,4-dinitrophenylhydrazones from 95% ethanol.

Diels–Alder Reactions. The reactions and their workup followed a previous prescription[7a] and the conditions are detailed in Table V.

Octalone 3b: IR 3037 (w, olefinic CH), 1720 (s, C=O), 1680 (w, C=C) cm^{-1}; ^{1}H NMR δ 1.04 (d, 3, J = 5 Hz, 3-Me), 1.60 (s, 3, 6-Me), 5.21 (br s, 1, H-7). Anal. Calcd for $C_{12}H_{18}O$: C, 80.85; H, 10.18. Found: C, 81.12; H, 10.16.

Octalone 3c: IR 3023 (w, olefinic CH), 1717 (s, C=O), 1672 (w, C=C) cm^{-1}; ^{1}H NMR δ 1.00 (d, 3, J = 5 Hz, Me), 1.17 (d, 3, J = 7 Hz, Me), 5.41 (m, 2, H-6, H-7). Anal. Calcd for $C_{12}H_{18}O$: C, 80.85; H, 10.18. Found: C, 80.86; H, 10.17.

Octalone 4b: IR 3030 (w, olefinic CH), 1714 (s, C=O), 1675 (w, C=C) cm^{-1}; ^{1}H NMR δ 0.95 (d, 3, J = 7 Hz, 3-Me), 1.62 (s, 3, 6-Me), 5.30 (br s, 1, H-7). Anal. Calcd for $C_{12}H_{18}O$: C, 80.85; H, 10.18. Found: C, 81.27; H, 10.21.

Octalone 4c: mp 42–43 °C; IR 3020 (w, olefinic CH), 1714 (s, C=O), 1655 (w, C=C) cm^{-1}; ^{1}H NMR δ 0.95, 0.97 (d, 3 each, J = 6 Hz, methyls), 5.45 (m, 2, H-6, H-7). Anal. Calcd for $C_{12}H_{18}O$: C, 80.85; H, 10.18. Found: C, 80.93; H, 10.20. 2,4-Dinitrophenylhydrazone: mp 164–165 °C. Anal. Calcd for $C_{18}H_{22}O_4N_4$: C, 60.32; H, 6.19; N, 15.63. Found: C, 60.21; H, 6.21; N, 15.65.

Octalone 6c: IR 3020 (w, olefinic CH), 1713 (s, C=O), 1655 (w, C=C) cm^{-1}; ^{1}H NMR δ 0.95, 1.00 (s, 3 each, J = 6 Hz, methyls), 5.26, 5.41 (br s, 1 each, H-6, H-7). Anal. Calcd for $C_{12}H_{18}O$: C, 80.85; H, 10.18. Found: C, 80.72; H, 10.22.

(17) The nonisolated products of the reactions of the **1a–2a**, **1b–2a**, **1b–2b**, **1c–2b**, and **1c–2c** reactant pairs (footnotes b and e of Table I) are assumed to be derived from syn[18] attack by analogy with the formation of products **6c**, **10a**, **14a**, and **14b** in the reactions of the **1c–2a**, **1a–2b**, **1a–2c**, and **1b–2c** pairs of reactants, respectively.

(18) The terms syn and anti in the context of the Diels–Alder reaction are introduced herewith to distinguish the relationship of the dienophile side chain to the diene in the cycloaddition complex. Syn implies a diene attack on the dienophile on the side of the substituent, while anti refers to an interaction on the opposite face.

(19) It was difficult to obtain more data on uncatalyzed Diels–Alder reactions in view of the thermal instability of many of the products.

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[d]	3	0.9	0.1	70	11	80
1a–2b	3	0.5	0.1	60	25	81
1a–2c	15	0.9	0.2	25	44	97
1b–2a	9	0.25	0.1	40	18	72
1b–2b	9	0.25	0.1	25	14	75
1b–2c	15	0.1	0.2	25	24	92
1c–2a	3	0.25	0.1	40	34	80
1c–2b	3	0.5	0.1	40	5	84
1c–2c	9	0.5	0.1	40	2	91

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

Octalone 7a: IR 3030 (w, olefinic CH), 1716 (s, C=O), 1660 (w, C=C), 1389, 1369 (m, $CHMe_2$) cm^{-1}; ^1H NMR δ 0.92 (d, 6, J = 6 Hz, Me_2), 5.44 (m, 2, H-6, H-7). Anal. Calcd for $C_{13}H_{20}O$: C, 81.20; H, 10.50. Found: C, 81.36; H, 10.52.

Octalone 7b: IR 3035 (w, olefinic CH), 1714 (s, C=O), 1675 (w, C=C), 1388, 1370 (m, $CHMe_2$) cm^{-1}; ^1H NMR δ 0.94 (d, 6, J = 6 Hz, *i*-Pr Me_2), 1.60 (s, 3, 6-Me), 5.21 (m, 1, H-7). Anal. Calcd for $C_{14}H_{22}O$: C, 81.50; H, 10.74. Found: C, 81.52; H, 10.70.

Octalone 7c: IR 3015 (w, olefinic CH), 1710 (s, C=O), 1665 (w, C=C), 1385, 1365 (m, $CHMe_2$) cm^{-1}; ^1H NMR δ 0.92 (d, 6, J = 6 Hz, *i*-Pr Me_2), 1.16 (d, 3, J = 7 Hz, 8-Me), 5.35 (br s, 2, H-6, H-7). Anal. Calcd for $C_{14}H_{22}O$: C, 81.50, H, 10.74. Found: C, 81.71; H, 10.73.

Octalone 8a: IR 3030 (w, olefinic CH), 1713 (s, C=O), 1650 (w, C=C), 1388, 1369 (m, $CHMe_2$) cm^{-1}; ^1H NMR δ 0.90, 0.94 (d, 3 each, J = 5 Hz, Me_2), 5.54 (br s, 2, H-6, H-7). Anal. Calcd for $C_{13}H_{20}O$: C, 81.20; H, 10.50. Found: C, 80.64; H, 10.43.

Octalone 8b: IR 3030 (w, olefinic CH), 1714 (s, C=O), 1680 (w, C=C), 1388, 1369 (m, $CHMe_2$) cm^{-1}; ^1H NMR δ 0.90, 0.98 (d, 3 each, J = 5 Hz, Me_2), 1.62 (s, 3, 6-Me), 5.33 (m, 1, H-7). Anal. Calcd for $C_{14}H_{22}O$: C, 81.50; H, 10.74. Found: C, 81.50; H, 10.72.

Octalone 8c: IR 3022 (w, olefinic CH), 1715 (s, C=O), 1675 (w, C=C), 1388, 1368 (m, $CHMe_2$) cm^{-1}; ^1H NMR δ 0.90, 0.94 (d, 3 each, J = 5 Hz, Me_2), 0.96 (d, 3, J = 7 Hz, 8-Me), 5.41 (m, 2, H-6, H-7). Anal. Calcd for $C_{14}H_{22}O$: C, 81.50; H, 10.74. Found: C, 81.60; H, 11.13.

Octalone 10a: IR 3025 (w, olefinic CH), 1713 (s, C=O), 1665 (w, C=C), 1389, 1370 (m, $CHMe_2$) cm^{-1}; ^1H NMR δ 0.95 (d, 6, J = 5 Hz, Me_2), 5.60 (m, 2, H-6, H-7). Anal. Calcd for $C_{13}H_{20}O$: C, 81.20; H, 10.50. Found: C, 81.12; H, 10.40.

Octalone 11a: mp 44–45 °C; IR 3030 (w, olefinic CH), 1715 (s, C=O), 1661 (w, C=C), 1389, 1369 (m, CMe_3) cm^{-1}; ^1H NMR δ 0.91 (s, 9, Me_3), 5.48 (m, 2, H-6, H-7). Anal. Calcd for $C_{14}H_{22}O$: C, 81.50; H, 10.74. Found: C, 81.35; H, 10.62.

Octalone 11b: IR 3015 (w, olefinic CH), 1715 (s, C=O), 1680 (w, C=C), 1395, 1368 (m, CMe_3) cm^{-1}; ^1H NMR δ 0.92 (s, 9, Me_3), 1.60 (br s, 3, 6-Me), 5.20 (br s, 1, H-7). Anal. Calcd for $C_{15}H_{24}O$: C, 81.76; H, 10.98. Found: C, 81.43; H, 10.82.

Octalone 11c: mp 52–53 °C; IR 3019 (w, olefinic CH), 1716 (s, C=O), 1650 (w, C=C), 1394, 1366 (m, CMe_3) cm^{-1}; ^1H NMR δ 0.91 (s, 9, Me_3), 1.15 (d, 3, J = 7 Hz, 8-Me), 5.39 (br s, 2, H-6, H-7). Anal. Calcd for $C_{15}H_{24}O$: C, 81.76; H, 10.98. Found: C, 81.73; H, 10.72.

Octalone 12a: IR 3025 (w, olefinic CH), 1715 (s, C=O), 1634 (w, C=C), 1398, 1369 (m, CMe_3) cm^{-1}; ^1H NMR δ 0.92 (s, 9, Me_3), 5.62 (br s, 2, H-6, H-7). Anal. Calcd for $C_{14}H_{22}O$: C, 81.50; H, 10.74. Found: C, 81.60; H, 10.70.

Octalone 12c: IR 3020 (w, olefinic CH), 1712 (s, C=O), 1645 (w, C=C), 1395, 1366 (m, CMe_3) cm^{-1}; ^1H NMR δ 0.90 (s, 9, Me_3), 0.99 (d, 3, J = 7 Hz, 8-Me), 5.40 (m, 2, H-6, H-7). Anal. Calcd for $C_{15}H_{24}O$: C, 81.76; H, 10.98. Found: C, 81.68; H, 10.93.

Octalone 14a: mp 59–60 °C; IR 3015 (w, olefinic CH), 1712 (s, C=O), 1655 (w, C=C), 1397, 1369 (m, CMe_3) cm^{-1}; ^1H NMR δ 0.92 (s, 9, Me_3), 5.62 (m, 2, H-6, H-7). Anal. Calcd for $C_{14}H_{22}O$: C, 81.50; H, 10.74. Found: C, 81.40; H, 10.50.

Octalone 14b: IR 3010 (w, olefinic CH), 1715 (s, C=O), 1680 (w, C=C), 1395, 1369 (m, CMe_3) cm^{-1}; ^1H NMR δ 0.90 (s, 9, Me_3), 1.62 (s, 3, 6-Me), 5.39 (m, 1, H-7). Anal. Calcd for $C_{15}H_{24}O$: C, 81.76; H, 10.98. Found: C, 81.80; H, 10.93.

Hydrogenation of Diels–Alder Adducts. A mixture of 200 mg of octalone and 20 mg of platinum oxide in 10 mL of dry ethanol was hydrogenated at room temperature and atmospheric pressure and the reaction terminated upon the consumption of an equimolar amount of hydrogen. The workup followed normal procedure.

Decalone 15: IR 1712 (s, C=O) cm^{-1}; ^1H NMR δ 0.99 (d, 3, J = 5 Hz, Me), 1.10 (d, 3, J = 6 Hz, Me). Anal. Calcd for $C_{12}H_{20}O$: C, 79.94; H, 11.18. Found: C, 80.08; H, 11.17.

Decalone 16: mp 34–35 °C; IR 1709 (s, C=O) cm^{-1}; ^1H NMR δ 0.89 (d, 3, J = 5 Hz, Me), 0.95 (d, 3, J = 7 Hz, Me). 2,4-Dinitrophenylhydrazone: mp 189–190 °C. Anal. Calcd for $C_{18}H_{24}O_4N_4$: C, 59.98; H, 6.71; N, 15.54. Found: C, 59.92; H, 6.70; N, 15.38.

Decalone 17: IR 1713 (s, C=O), 1389, 1370 (m, $CHMe_2$) cm^{-1}; ^1H NMR δ 0.92 (d, 6, J = 6 Hz, Me_2). Anal. Calcd for $C_{13}H_{22}O$: C, 80.35; H, 11.41. Found: C, 80.25; H, 11.37.

Decalone 18: IR 1710 (s, C=O), 1387, 1370 (m, $CHMe_2$) cm^{-1}; ^1H NMR δ 0.90, 0.97 (d, 3 each, J = 5 Hz, Me_2). Anal. Calcd for $C_{13}H_{22}O$: C, 80.35; H, 11.41. Found: C, 80.38; H, 11.40.

Decalone 19: mp 58–59 °C; IR 1715 (s, C=O), 1397, 1369 (m, CMe_3) cm^{-1}; ^1H NMR δ 0.89 (s, 9, Me_3). Anal. Calcd for $C_{14}H_{24}O$: C, 80.71; H, 11.61. Found: C, 80.81; H, 11.87.

Decalone 20: mp 31–32 °C; IR 1710 (s, C=O), 1394, 1365 (m, CMe_3) cm^{-1}; ^1H NMR δ 0.88 (s, 9, Me_3), 1.12 (d, 3, J = 6 Hz, 8-Me). Anal. Calcd for $C_{15}H_{26}O$: C, 81.02; H, 11.78. Found: C, 80.27; H, 11.80.

Decalone 21: IR 1710 (s, C=O), 1396, 1367 (m, CMe_3) cm^{-1}; ^1H NMR δ 0.89 (s, 9, Me_3), 0.96 (d, 3, J = 6 Hz, Me). Anal. Calcd for $C_{15}H_{26}O$: C, 81.02; H, 11.78. Found: C, 81.11; H, 11.77.

Epimerization of Diels–Alder Adducts. A 0.1 M solution (6 mL) of sodium ethoxide in dry ethanol was added to a solution of 40 mg of cis and/or trans bicyclic ketone in 8 mL of absolute ethanol under nitrogen and the mixture was stirred at 22 °C for a length of time needed to establish equilibrium (as monitored by GC analysis).

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