for 10 min and then passed into the chromatography chamber to wet the alumina. The reaction flask was then charged with 0.5 mL of dimethyl ether and 2 mL of pentane. The hydrazine (0.1–0.5 mmol) was added in 0.5 mL of pentane, followed by 1.5 equiv of triethylamine. The solution was deaerated for 10 min. Then *tert*-butyl hypochlorite (1.1 equiv) was slowly added, and the apparatus was agitated following the addition of each drop of oxidant. The reaction was allowed to proceed for 1 h, and the reaction mixture was then passed into the chromatography chamber. Elution from the column was assisted with nitrogen pressure. The column was washed once with 5 mL of 4:1 pentane–dimethyl ether and once with 5 mL of 1:1 pentane–dimethyl ether. Pure dimethyl ether was passed through the column until the pink diazene band was near the bottom of the alumina column. The chromatography was halted and the receiver was changed. The elution was continued with dimethyl ether until the entire pink band had been collected in the fresh receiver. The apparatus was then removed from the frozen pentane bath, and the receiver was immediately immersed in liquid nitrogen to freeze its contents. The receiver was carefully disconnected from the chromatography chamber and topped with a gas inlet adapter.

Decomposition of Diazene. Purified solutions of diazene in dimethyl ether or dimethyl ether–pentane mixtures were irradiated at −130 °C with a 450-W Hanovia medium-pressure mercury lamp or with a 150-W compact arc xenon lamp with an elliptical reflector. All reactions were analyzed after they were warmed to room temperature and the volatile solvents vented. (The reaction chemistry of the 1,1-disubstituted diazene does not appear to be affected by the presence of impurities resulting from its preparation. Preliminary qualitative results were therefore obtainable from the study of crude, unchromatographed diazene preparations. These solutions were prepared in the cells to be used for irradiation.) Thermal decomposition (in a pentane bath held at −90 °C by the addition of liquid nitrogen) and direct irradiation (−130 °C, $\lambda > 330$ nm) of **4** yielded products **16–19** (Table I). Data for **16**: IR 3098, 2971, 2865, 2220, 1616, 1476, 1456, 1372, 1362, 1307, 1240, 1204, 894 cm^{-1}; ^1H NMR (300 MHz) δ 1.24 (s, 9 H), 1.86 (t, J = 1 Hz, 3 H), 5.11–5.13 (m, 1 H), 5.17, 5.19 (m, 1 H); MS m/z 122.1114 (M^+, calcd for C_9H_{14} 122.1092). Data for **17**: IR 2968, 2900, 2866, 1475, 1464, 1455, 1382, 1371, 1361, 1296, 1263, 1204, 1145, 1104, 996, 987 cm^{-1}; ^1H NMR (500 MHz) δ 0.95 (s, 3 H), 1.17 (s, 3 H), 1.19 (s, 9 H), 1.20 (s, 3 H), 1.59–1.75 (m, 3 H), 2.04–2.11 (m, 1 H); MS m/z 178.1698 (M^+, calcd for $C_{13}H_{22}$ 178.1720). Anal. ($C_{13}H_{22}$) C, H. Data for **18** and **19** (purified mixture): IR 3075, 2969, 2931, 2869, 1649, 1456, 1375, 1362, 1334, 1265, 1205, 890 cm^{-1}; ^1H NMR (normalized on singlet at δ 1.19 [*tert*-butyl protons of **19**] = 9 H) (500 MHz) δ 0.89 (d, J = 6.5 Hz, 0.9 H), 1.12 (d, J = 6.9 Hz, 3 H), 1.19 (s, 9 H), 1.24 (s, 1.3 H), 1.35–1.42 (m, 0.3 H), 1.46–1.54 (m, 2 H), 1.73 (s, 3 H), 1.81–1.82 (m, 0.1 H), 2.03–2.21 (m, 2.3 H), 2.33–2.42 (m, 1 H), 4.68–4.72 (m, 2 H), 5.10–5.12 (m, 0.1 H), 5.17–5.19 (m, 0.1 H); MS m/z 178.1728 (M^+, calcd for $C_{13}H_{22}$ 178.1720).

Reaction of (3,3-Dimethyl-1-butynyl)magnesium Bromide with Acetone and Dehydration. 2,5,5-Trimethyl-1-hexen-3-yne (16). (3,3-Dimethyl-1-butynyl)magnesium bromide, prepared as described above from 3,3-dimethyl-1-butyne (500 mg), was allowed to react with acetone (550 mg) in the usual manner. Workup with ether and acid gave crude 2,5,5-trimethyl-3-hexyn-2-ol. This was treated directly with thionyl chloride (1.15 g) in pyridine (4 mL) at 0 °C, followed by warming to room temperature over 3 h. The reaction mixture was worked up with pentane and water, and preparative vapor-phase chromatography gave authentic **16**, the properties of which were essentially identical with those given above. The NMR spectrum was in good agreement with that previously recorded for unpurified **16**.[9]

Acknowledgment. We thank the National Science Foundation and the donors of the Petroleum Research Fund, administered by the American Chemical Society, for support of this research. We thank S. T. Bella for microanalyses and Laura Mieszerski for technical assistance. High-field NMR spectra were determined by Francis Picart and Julie Wu on instruments purchased with funds from the National Science Foundation, the National Institutes of Health, and the Keck Foundation. Mass spectra were performed by The Rockefeller University Mass Spectrometric Biotechnology Research Resource.

Stabilization Energy of Polyenyl Radicals: *all-trans*-Nonatetraenyl Radical by Thermal Rearrangement of a Semirigid {4-1-2} Heptaene. Model for Thermal Lability of β-Carotene

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Abstract: Evaluation of the stabilization energy of the nonatetraenyl radical directly from the enthalpy of activation of the thermal anti–syn rearrangement of a semirigid nonaene having a symmetrical distribution {4-1-4} of double bonds is thwarted by insolubility. Indirect comparison of the enthalpy of activation of an unsymmetrical {4-1-2} heptaene with that of an already determined symmetrical {2-1-2} pentaene leads to an inferred enthalpy of activation of 24.5 kcal/mol for the {4-1-4} nonaene. Perhaps the point of greatest theoretical interest is the rapidity with which successive increments in stabilization energies (SE_n) decrease with increasing number of double bonds in the conjugated polyenyl radicals. Values of SE_n for n = 1 (allyl), 2 (pentadienyl), 3 (heptatrienyl), and 4 (nonatetraenyl) are 13.5, 16.9, 19.2, and 20.7 kcal/mol, respectively.

In an initial paper,[1] stabilization enthalpies of the pentadienyl and heptatrienyl radicals have been estimated from activation parameters for the thermal anti–syn isomerization about the central double bond of a {1-1-1} hexatriene $\mathbf{1}_{1.1.1}$, a {2-1-2} decapentaene $\mathbf{2}_{2.1.2}$, and a {3-1-3} tetradecaheptaene $\mathbf{3}_{3.1.3}$ (see Table III). In a second paper,[2] solvent friction has been tentatively recognized as a small factor, which may serve as a warning against uncritical transfer to the gas phase of data acquired in solution. In the present paper, determination of the stabilization enthalpy of the nonatetraenyl radical extends the series far enough to permit the tentative conclusions that the experimental enthalpies of activation agree best with the theoretical values of Saïd, Maynau, Malrieu, and Garcia Bach[3] and that *all-trans*-β-carotene (11 double bonds) should rearrange slowly at physiological temperature

(1) Doering, W. von E.; Kitagawa, T. *J. Am. Chem. Soc.* **1991**, *113*, 4288–4297.

(2) Doering, W. von E.; Birladeanu, L.; Cheng, X-h.; Kitagawa, T.; Sarma, K. *J. Am. Chem. Soc.* **1991**, *113*, 4558–4563.

(3) Saïd, M.; Maynau, D.; Malrieu, J.-P.; Garcia Bach, M.-A. *J. Am. Chem. Soc.* **1984**, *106*, 571–579.

0002-7863/92/1514-6037$03.00/0

Scheme I

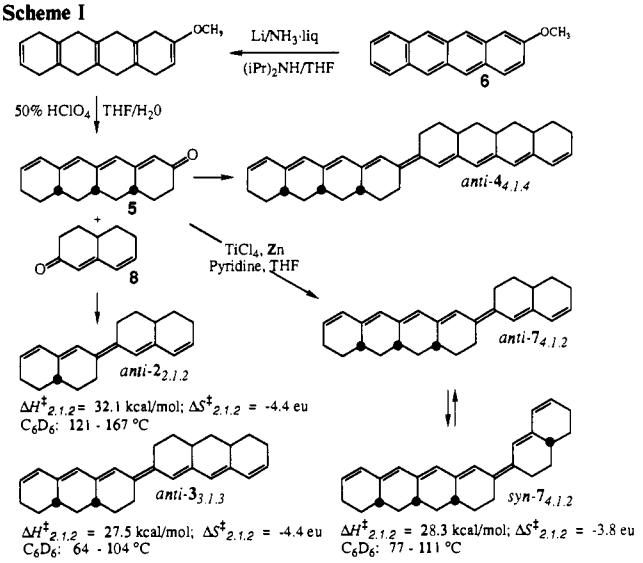


Table I. Thermal Isomerization of *anti-* and *syn*-$7_{4.1.2}$ in Benzene-d_6: Specific Rate and Equilibrium Constants and Activation Parameters

T, °C	k, $\times 10^{-6}$ s^{-1}	K
77.2 ± 0.1	2.28 ± 0.04	0.390
87.6 ± 0.2	7.63 ± 0.12	0.406
101.5 ± 0.1	33.4 ± 1.0	0.425
111.2 ± 0.1	91.9 ± 3.9	0.443
111.2 ± 0.1	95.9 ± 4.2	0.442

Arrhenius Plot [$1/T$ vs log k]
E_a = 29.07 ± 0.04 kcal/mol
log A = 12.50 ± 0.02

Eyring Parameters
$\Delta H^{\ddagger}_{4.1.2}$ = 28.3 ± 0.04 kcal/mol
$\Delta S^{\ddagger}_{4.1.2}$ = −3.8 ± 0.10 eu

Thermodynamics [$1/T$ vs log K]
$\Delta H°$ = 0.98 ± 0.03 kcal/mol
$\Delta S°$ = 0.92 ± 0.09 eu

to its 15-cis and 13-cis isomers.

The Nonatetraenyl Radical. Synthesis of the {4-1-4} octadecanonaene $4_{4.1.4}$ and the evaluation of its activation parameters were expected to proceed uneventfully (see Scheme I). The requisite tetraenone **5** was prepared from β-methoxynaphthacene (**6**) by a method similar to that used previously for the analogous dienone and trienone.[1] Birch reduction of **6** and acid-catalyzed hydrolysis and rearrangement of double bonds into conjugation produced **5** in satisfactory yield as a single stereoisomer having the thermodynamically favored syn,syn configuration. Mukaiyama–Tyrlik–McMurry reductive coupling[4] of **5** then afforded the desired nonaene **4**, which, to our distress, was too sparingly soluble to be useful in kinetic studies that employed NMR spectroscopy as the analytical tool.

This unfortunate obstacle has been circumnavigated by synthesizing a polyene of lower symmetry that retained the requisite {4-1-*n*} feature in more soluble form. Reductive coupling of a mixture of tetraenone **5** and dienone **8**, as visualized in Scheme I, affords, inter alia, $7_{4.1.2}$, which precourses a pentadienyl and a nonatetraenyl radical at the 90° stage of anti–syn rearrangement. Extraction of the stabilization enthalpy of the nonatetraenyl radical from the kinetic behavior of this unsymmetrical heptaene demands acceptance of the same assumption of independently contributed stabilization by each radical at the 90° twisted transition state basic to the entire approach, namely that polyenes of the type

(4) (a) Mukaiyama, T.; Sato, T.; Hanna, J. *Chem. Lett.* **1973**, 1041–1044. Mukaiyama, T.; Ishida, A. *Chem. Lett.* **1976**, 1127–1130. (b) Tyrlik, S.; Wolochowicz, I. *Bull. Soc. Chim. Fr.* **1973**, 2147–2148. (c) McMurry, J. E.; Fleming, M. P. *J. Am. Chem. Soc.* **1974**, *96*, 4708–4709. McMurry, J. E. *Chem. Rev.* **1989**, *89*, 1513–1524.

Table II. Kinetic Data from Thermal Isomerization of *anti*-$7_{4.1.2}$ to *syn*-$7_{4.1.2}$ in Benzene-d_6

111.2 ± 0.1 °C		101.5 ± 0.1 °C		87.6 ± 0.2 °C		77.2 ± 0.1 °C	
t, s	% syn[a]	t, s	% syn[a]	t, s	% syn[a]	t, s	% syn[a]
0	1.39	0	0.77	0	1.37	0	5.92
750	7.39	3600	11.81	7200	6.37	14400	8.75
1650	13.80	7200	17.23	14400	10.63	63000	15.37
2850	18.79	14400	23.68	21600	13.46	97200	18.10
4050	21.83	21600	27.02	30900	16.89	156600	21.89
6000	26.10	28800	28.80	43200	20.07	212400	23.82
10200	29.85	37800	29.60	59400	23.14	349200	26.83
16200	30.23	52200	30.12	77400	25.08	608400	27.84
22200	30.65			106200	27.37	910800	28.24
				146200	27.97		
				191700	29.16		

[a] Parent anti = 100 − percent syn.

Table III. Enthalpies and Entropies of Activation of Anti–Syn Isomerization of Polyenes of Order $2n + 1$, Enthalpies of Stabilization, SE_n, and Derived Heats of Formation of Polyenyl Radicals of Type $H_2C{=}CH(CH{=}CH)_nCH_2^{\cdot}$ (n = 1–4)

	$\Delta H^{\ddagger}_{n.1.n}$[a]	$\Delta S^{\ddagger}_{n.1.n}$[b]	$\Delta\Delta H^{\ddagger}$[c]	SE_n[a]	$\Delta_f H^{\cdot}_n$[a]
n = 0 {0-1-0}	[58.1$_{(g)}$]		19.2		
1 n = 1 {1-1-1}	38.9	- 2.9	6.8	13.5	+39.9
2 n = 2 {2-1-2}	32.1	- 4.4	4.6	16.9	+49.6
3 n = 3 {3-1-3}	27.5	- 4.4	3.0	19.2	+60.7
4 n = 4 {4-1-4}	24.5			20.7	+72.6

[a] kcal/mol. [b] cal/(mol deg). [c] $\Delta\Delta H^{\ddagger}_{(n-1).1.(n-1)} - \Delta\Delta H^{\ddagger}_{n.1.n}$.

{x-1-y} ($x = y$) may be used for estimation of stabilization energies of radicals of the structure •CHX.

Study of the kinetics of the anti–syn rearrangement of $7_{4.1.2}$ follows the procedure described for the symmetrical heptaene, $3_{3.1.3}$.[1] Rate constants and derived Arrhenius parameters, given in Table I, are based on the experimental data of Table II. From the enthalpy of activation of *anti*-$7_{4.1.2}$, $\Delta H^{\ddagger}_{4.1.2}$ = 28.3 ± 0.1 kcal/mol, and that of *anti*-$2_{2.1.2}$, $\Delta H^{\ddagger}_{2.1.2}$ = 32.1 ± 0.4 kcal/mol,[1] an enthalpy of activation for the rearrangement of *anti*-$4_{4.1.4}$ can be calculated to be 24.5 kcal/mol by the equation [(32.1 + $\Delta H^{\ddagger}_{4.1.4}$) = 2(28.3)]. We are encouraged in this approach by the constancy of entropies of activation in the series, compounds **2**, **3**, and **7** having values of −4.4, −4.4, and −3.8 eu, respectively, and by the enthalpy of activation of **3** being higher than that of **7** by 0.8 kcal/mol (vide infra).

Arrhenius parameters for the series of thermal, anti–syn isomerizations as related to the number of double bonds in the congeneric polyenyl radicals are collected in Table III. The trend toward diminishing return inferred previously[1] is confirmed with this extension to the nonatetraenyl radical and is highlighted by noting the differences in enthalpies of activation between each successive member (column 4 of Table III).

Stabilization Enthalpies of Polyenyl Radicals. As previously elaborated,[1] stabilization enthalpy of a polyenyl radical is defined not as *total* π-electron stabilization but as that stabilization limited to delocalization of the odd electron of the radical. Total stabilization enthalpy additionally includes an enthalpy of conjugation in the starting polyene of magnitude $(n-1)K$[5] and becomes infinite in a polyenyl radical of infinite order. Allyl, the first member

(5) K, the Kistiakowsky, is the enthalpy of conjugation between two coplanar double bonds and is considered a constant independent of order of the polyene, as outlined previously.[1]

of the series of polyenyl radicals, has a stabilization enthalpy, SE_1, which determines that of the others through eq 1, where n is the

$$SE_n = SE_1 + (\Delta H^{\ddagger}_{1.1.1} - \Delta H^{\ddagger}_{n.1.n})/2 \quad (1)$$

number of double bonds in the polyenyl radical and $\Delta H^{\ddagger}_{n.1.n}$ is the enthalpy of activation of anti–syn rearrangement about the central double bond in an $\{n.1.n\}$ polyene of $(2n + 1)$ double bonds. For the first {1-1-1} polyene in the series, triene **1** (see Table III), three values for $\Delta H^{\ddagger}_{1.1.1}$ may be considered: that of Kitagawa in benzene solution—38.9 kcal/mol, $\Delta S^{\ddagger}_{1.1.1} = -6.0$ eu;[1] that of Roth et al. in the gas phase—40.9 kcal/mol, $\Delta S^{\ddagger}_{1.1.1} = -1.7$ eu;[6] and an unpublished solution value of Zhao for 4,4′-bi-1-methylbicyclo[4.4.0[1,6]]dec-5-enylidene—40.1 kcal/mol, $\Delta S^{\ddagger}_{1.1.1} = -4.3$ eu.[7] This latter example has merit because of its closeness in structure to the second {2-1-2} polyene, pentaene **2**. Various values for the parent, unsubstituted hexa-1,3,5-triene, are in the literature.[8-10] We have decided tentatively to use the Kitagawa solution value of $\Delta H^{\ddagger}_{1.1.1}$ for comparison with the other values in the series, despite the greater precision obtained in the gas-phase experiments.[10,11] The choice is conditioned less by a concern for the resulting value of allylic stabilization (SE_1), which is not the focus of this work and for which a currently "best" value of 13.5 kcal/mol has recently been advanced,[6,11] than it is with internal consistency (note that the choice by the reader of any other value for SE_1, as circumstances might seem to warrant, is quite permissible and would alter the absolute values of SE_n but not the differences among them).

Among other points made in the prior exposition,[1] we recall the following. The absolute value of SE_1 is not directly comparable to values of SE_n because it is defined as stabilization enthalpy associated with replacement of alkyl (sp^3–sp^2 bond) by vinyl (sp^2–sp^2 bond), i.e. $CH_2{=}CHCH_2^{\bullet}$ vice $CH_3CH_2CH_2^{\bullet}$, whereas SE_2 and higher involve replacement of sp^2–sp^2 bonds by bonds of the same type; i.e. $CH_2{=}CH(HC{=}CH)_nCH_2^{\bullet}$ vice $CH_2{=}CH(HC{=}CH)_{n-1}CH_2^{\bullet}$. It follows that all SE_n, as here defined, relate to replacement of *alkyl* by polyene. If values for replacement of *hydrogen* by polyene be preferred, $(SE_n)_{methane}$, e.g. $CH_2{=}CHCH_2^{\bullet}$ vice $HCH_2^{\bullet}$,[12,13] then the difference in bond dissociation energy between methane and ethane is added to SE_1 (and by definition to all SE_n). From Gutman's "best" values, that increment amounts to +4.4 kcal/mol.[14]

Implicit in the use of eq 1 is the widely held assumption that conjugative interaction between double bonds is an additive constant, K, whose value of 3.74 kcal/mol, the mean of values from several butadienes[15] and one triene,[16] is independent of the order of the polyene. There is theoretical, but no further experimental, support for this assertion.[17-19] We had hoped to determine heats of hydrogenation of our polyenes, but uptake of hydrogen was not quantitative, presumably owing to the presence of tetrasubstituted double bonds.

Can our values for SE_n for n = 1–4 (Table III) be used to estimate values for SE_n when $n \geq 5$? A function relating n and SE_n has to be defined arbitrarily, for it can scarcely be discovered from only three experimental values of $\Delta\Delta H^{\ddagger}$. A fourth difference, from activation parameters for a {5-1-5} undecaene, would improve matters but little; possibly a fifth difference would begin to suffice.

Despite this strong admonition, a simple, intuitively acceptable, geometric progression represented by eq 2 might be justified for prediction of the next higher homologs

$$\Delta H^{\ddagger}_{n.1.n} = \Delta H^{\ddagger}_{1.1.1} - a(1 - r^{n-1})/(1 - r) \quad (2)$$

where n and $2n + 1$ are the number of double bonds in the polyenyl radical and polyene, respectively, $a = \Delta H^{\ddagger}_{1.1.1} - \Delta H^{\ddagger}_{2.1.2} = 6.8$ kcal/mol, and $\Delta H^{\ddagger}_{1.1.1} = 38.9$ kcal/mol. From the four values of $\Delta H^{\ddagger}_{n.1.n}$ in column 2 of Table III [whence the three values for $\Delta\Delta H^{\ddagger}$ in column 4], a mean value of $r = 0.67$ is obtained. Thence values of $\Delta H^{\ddagger}_{5.1.5}$, $\Delta H^{\ddagger}_{6.1.6}$, and $\Delta H^{\ddagger}_{7.1.7}$ equal to 22.4, 21.2, and 20.2 kcal/mol, respectively, can be estimated.

Although extrapolation to $n = \infty$ on the basis of assumed function 2 is even less justified, qualitatively, $\Delta H^{\ddagger}_{\infty}$ does not appear to be headed for zero. Application of eq 2 leads to values for $\Delta H^{\ddagger}_{\infty}$ and SE_{∞} of 18.3 and 23.8 kcal/mol, respectively.

That each successive double bond should contribute substantially less to SE_n comes as a surprise to one who had accepted the several higher values for SE_2 offered in the literature.[1] Indeed, the highest of these (25.0 kcal/mol) led to a predicted value of $\Delta H^{\ddagger}_{2.1.2} = 15.9$ kcal/mol for a pentaene [38.9 − 2(25 − 13.5)] and reasonably to a value of $\Delta H^{\ddagger}_{4.1.4}$ close to 0 kcal/mol for a nonaene such as β-carotene, which then could have been as well represented by a 90° twisted diradical as by a coplanar nonaene.

Qualitatively, our estimates of enthalpies of activation for polyenes of higher order are quite consistent with the observations of Knoll and Schrock[20] that their *tert*-butyl-capped polyenes of order $(2n + 1)$ and stereochemically of type trans(cis,trans)$_n$ rearrange thermally (3 min each from 120 to 195 °C at 15° intervals). From polyene of order 5, which rearranges at a barely perceptible rate at 195 °C, there is a regular increase in rate with order. By polyene of order 15, the rate is so fast as to interfere with isolation in pure form.

Comparison with Theory. Theoretical predictions relate to *unsubstituted* polyenes and to enthalpies of activation in the *gas phase* and are not fully commensurate with our experimental system, which relates to more highly *alkyl-substituted* polyenes in *solution*.

With respect to substitution, the heats of formation of the simplest 1°, 2°, and 3° radicals of Gutman[14] can be recast to reveal the relative interaction of methyl groups with the sp^2 carbon atoms of an olefin and a free radical. Examination of the hypothetical heats of three semi-hydrogenations reveals no dependence within experimental uncertainties on substitution in the simplest systems:

$$CH_2{=}CH_2 + \tfrac{1}{2}H_2 \rightarrow CH_3CH_2^{\bullet} \qquad \Delta H_r = +15.7_2 \text{ kcal/mol}$$

$$CH_3CH{=}CH_2 + \tfrac{1}{2}H_2 \rightarrow (CH_3)_2CH^{\bullet} \qquad \Delta H_r = +16.5_2 \text{ kcal/mol}$$

$$(CH_3)_2C{=}CH_2 + \tfrac{1}{2}H_2 \rightarrow (CH_3)_3C^{\bullet} \qquad \Delta H_r = +15.6_4 \text{ kcal/mol}$$

An extensive investigation into the effect of alkyl substitution on energy of stabilization in the allyl radical similarly has revealed no systematic effect.[21] It remains to be seen whether the same insensitivity to pattern of substitution extends to the pentadienyl radical and beyond.

Speculation on the magnitude of a correction for the solution/gas-phase perturbation is unrewarding until more definitive

(6) Doering, W. von E.; Roth, W. R.; Bauer, F.; Boenke, M.; Breuckmann, R.; Ruhkamp, J.; Wortmann, O. *Chem. Ber.* **1991**, *124*, 1461–1470.
(7) Doering, W. von E.; Zhao, Da-chuan. Unpublished.
(8) Doering, W. von E.; Beasley, G. *Tetrahedron*, **1973**, *29*, 2231–2243: E_a = 43.3 kcal/mol; log A = 12.9.
(9) Orchard, S. W.; Thrush, B. A. *J. Chem. Soc., Chem. Commun.* **1973**, 14–15: E_a = 43.3 kcal/mol; log A = 12.65.
(10) Grimme, W.; Schumachers, L.; Roth, W. R.; Breuckmann, R. *Chem. Ber.* **1981**, *114*, 3197–3208: E_a = 45.5 kcal/mol; log A = 13.44.
(11) Roth, W. R.; Bauer, F.; Beitat, A.; Ebbrecht, T.; Wüstefeld, M. *Chem. Ber.* **1991**, *124*, 1453–1460.
(12) Davies, A. G.; Griller, D.; Ingold, K. U.; Lindsay, D. A.; Walton, J. C. *J. Chem. Soc., Perkin Trans. 2* **1981**, 633–641.
(13) Dewar, M. J. S.; Fox, M. A.; Nelson, D. J. *J. Organomet. Chem.* **1980**, *185*, 157–181.
(14) Seetula, J. A.; Russell, J. J.; Gutman, D. *J. Am. Chem. Soc.* **1990**, *112*, 1347–1353.
(15) (a) Cox, J. D.; Pilcher, G. *Thermochemistry of Organic and Organometallic Compounds*; Academic Press: London, 1970. (b) Pedley, J. B.; Naylor, R. D.; Kirby, S. P. *Thermochemical Data of Organic Compounds*, 2nd ed.; Chapman and Hall: London, 1986.
(16) Turner, R. B.; Mallon, B. H.; Tichy, M.; Doering, W. von E.; Roth, W. R.; Schröder, G. *J. Am. Chem. Soc.* **1973**, *95*, 8605–8610.
(17) Dewar, M. J. S.; deLlano, C. *J. Am. Chem. Soc.* **1969**, *91*, 789–802.
(18) Heilbronner, E.; Bock, H. *Das HMO-Modell und seine Anwendung*; Verlag Chemie: Weinheim, 1970; Vol. 3, pp 16–42.
(19) (a) Hess, B. A., Jr.; Schaad, L. J. *J. Am. Chem. Soc.* **1971**, *93*, 305–310. (b) Hess, B. A., Jr.; Schaad, L. J. *Pure Appl. Chem.* **1980**, *52*, 1471–1494.
(20) Knoll, K.; Schrock, R. R. *J. Am. Chem. Soc.* **1989**, *111*, 7989–8004.
(21) Roth, W. R.; Bauer, F.; Boenke, M.; Breuckmann, R.; Ruhkamp, J.; Wortmann, O. *Chem. Ber.* In preparation.

Table IV. Enthalpies of Activation, $\Delta H^{\ddagger}_{n.1.n}$, for Anti-Syn Rearrangements of Semirigid Polyenes of the Type $H(CH{=}CH)_nCH{=}CH(CH{=}CH)_nH$, Enthalpies of Stabilization, SE_n, and Heats of Formation, $\Delta_f H°_n$, of Polyenyl Radicals of the Type $H(CH{=}CH)_nCH_2^{\cdot}$

n	$\Delta H^{\ddagger}_{n.1.n}$ exp	$\Delta\Delta H^{\ddagger}$ exp	SE_n exp	$\Delta_f H°_n$ exp	$\Delta H^{\ddagger}_{n.1.n}$ HMO[b]	$\Delta_f H°_n$ nndoMO[c]	SE_n RE(SRT)[d]	$\Delta H^{\ddagger}_{n.1.n}$ HHMM[e]
0	{58.1}			**34.9**[14]	{58.1}	34.1		62.5
		19.2						
1	**38.9**		**13.5**[f]	**39.9**[11]	39.5	43.0	11.6	42.5
		6.8						
2	**32.1**		**16.9**	**49.6**[1]	33.4	54.4	17.8	34.0
		4.6						
3	**27.5**		**19.2**	**60.7**[1]	30.4	67.6	21.0	30.0
		3.0						
4	**24.5**		**20.7**	**72.6**[1]	28.6	81.4		27.0
		2.05						
5	*22.4*[g]				27.5			
		1.37						
6	*21.1*[g]				26.6			
		0.92						
7	*20.1*[g]				26.0			
∞	*18.4*[g]		*23.6*[g]					*18.2*

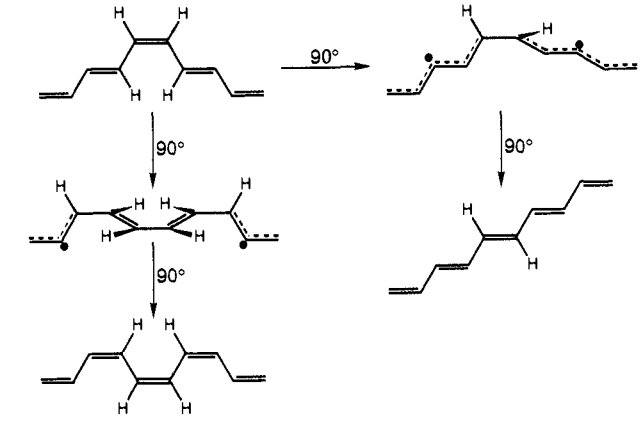
[a] All values in kcal/mol. [b] Rotational barriers about the central double bond in odd-membered polyenes calculated by simple Hückel molecular orbital theory.[18,19] [c] Heats of formation of polyenyl radicals calculated by the neglect of nonbonded differential overlap molecular orbital theory.[25] [d] Resonance energies of polyenyl radicals by an empirical, parametrized, valence-bond method.[26] [e] Rotational barriers calculated by a nonempirical Heisenberg Hamiltonian.[3] [f] This value for allyl stabilization is currently the "best" value; it would have been 13.4 if based on 58.1 for monoene (gas phase) and 38.9 kcal/mol for triene (solution). [g] On assumption, deus ex machina (see text), that $\Delta H^{\ddagger}_{n.1.n} = \Delta H^{\ddagger}_{1.1.1} - a(1 - r^{n-1})/(1 - r)$.

experimental results become available, particularly from longer polyenes of higher order. As far as it goes, our examination of extensivity as a factor capable of slowing rates reveals a small effect at worst.[2]

There are four published theoretical calculations of heats of formation or stabilization energies of polyenyl radicals,[22] from which predictions of activation enthalpies of rotation about a double bond in linear polyenes can be derived.[23,24] The Hückel molecular orbital (HMO) approach is advanced implicitly in the calculations of Heilbronner and Bock[18] and explicitly in two papers by Hess and Schaad.[19] Baird has calculated heats of formation by an MO method with neglect of nonbonded differential overlap.[25] A valence bond approach has been advanced by Herndon.[26] Most recently, Saïd, Maynau, Malrieu, and Garcia Bach[3] have had the insight to apply a magnetic Heisenberg Hamiltonian to the problem. The various theoretical results are juxtaposed the appropriate experimental results in Table IV. Those of Saïd et al. (column 9) are seen to be in excellent agreement with the experimental data (column 2), provided a constant displacement of 2.5 kcal/mol to lower values is applied. That this displacement might originate in the absence of substituents in the theoretical treatment is made plausible by noting that rearrangement of unsubstituted *trans*-hexa-1,3,5-triene to cyclohexadiene via *cis*-hexa-1,3,5-triene has a value of $\Delta H^{\ddagger}$ = 44.5 kcal/mol,[10] which is higher by 3.5–5.5 kcal/mol than those of the semirigid, substituted trienes noted above.

Consequences. We return briefly to the parameters brought to light in the rearrangements of unsymmetrical heptaene $\mathbf{7}_{4.1.2}$ and symmetrical heptaene $\mathbf{3}_{3.1.3}$, displayed in Scheme I. It is a necessary consequence of the decrease in value of $\Delta\Delta H^{\ddagger}$ found experimentally (shown in column 4 of Table III) and predicted theoretically by Saïd, Maynau, Malrieu, and Garcia Bach[3] that movement away from the center of a polyene as the site of thermal rearrangement will result in a larger loss in stabilization energy in the shortened radical than gain in stabilization energy in the longer radical. Experimental enthalpies of activation ($\Delta H^{\ddagger}_{3.1.3}$ = 27.5 kcal/mol; $\Delta H^{\ddagger}_{4.1.2}$ = 28.3 kcal/mol) and specific rate constants calculated at 100 °C (6.7 amd 3.0 × 10^{-5} s^{-1}, respectively) are fully consistent. This feature is expected to have important consequences for the kinetics of rearrangement about the various double bonds in β-carotene. As the site of the rotation moves further away from the center, rates are expected to decrease and enthalpies of activation to increase.

Scheme II



Internal Rotation of Groups. Of interest in the thermal chemistry of polyenes of higher order is the prediction that a pair of radical solitons[27] can be generated by internal rotation of a *group* of atoms as well as by twisting 90° about a single double bond. An example is given in Scheme II where a 90° rotation about a central cis double bond is compared with rotation of the planar four-atom, butadienyl group that includes a central cis double bond. There are two thermochemical differences between them: rotation of the butadienyl group is worse off by one K (3.74 kcal/mol) and by two times the difference between SE_1 and SE_2 (6.8 kcal/mol). In the illustrated example, rotation of the butadienyl group has an enthalpy of activation predicted to be higher by 10.6 kcal/mol. As the order of the polyene increases, the difference, $(SE_{n-1} - SE_n)$, becomes progressively smaller until it vanishes in the limit. The predicted difference between the two processes approaches a limiting value one K higher than the process of simple rotation about a double bond. The butadiene path for generation of a pair of radical solitons may have an advantage in close-packed polyenes like polyacetylenes because no movement of the bulk of the polyene is required. Only the *cis*-butadiene

(22) A difference of 2.3 kcal/mol between SE_1 and SE_2 has been calculated by Dewar, Fox, and Nelson[13] by the method of MINDO 3.

(23) Dewar, M. J. S.; Kohn, M. C. *J. Am. Chem. Soc.* **1972**, *94*, 2699–2704.

(24) Dewar and Kohn[23] calculate an enthalpy of activation of 47.5 kcal/mol for rotation in *trans*-hexa-1,3,5-triene in good agreement with experiment.

(25) Baird, N. C. *Can. J. Chem.* **1971**, *49*, 338–340.

(26) Herndon, W. *J. Org. Chem.* **1981**, *46*, 2119–2125.

(27) For a superlative investigation of model polyenyl carbanions and their relation to the carbanionic soliton, see: Tolbert, L. M.; Ogle, M. E. *J. Am. Chem. Soc.* **1990**, *112*, 9519–9527.

moiety is required to move and that so slightly that little resistance from the proximate environment (solvent friction) is to be expected.

Thermal Lability of β-Carotene. Long known to be thermally unstable (15 min at 195 °C gives rise to at least 17 products, including many identified geometrical isomers;[28] 24 h at 151 °C causes a fascinating sequence of thermal rearrangements culminating in a beautifully elucidated delivery of toluene inter alia and appropriately diminished polyenes[29]), β-carotene can now be expected on the basis of the thermal behavior of the model polyenes to undergo trans–cis rearrangement at temperatures as low as 37 °C. Determination of the kinetics of its reversible rearrangement to 15-*cis*- and 13-*cis*-β-carotene has confirmed this prediction.[30] The question raised for biochemical, medical, and epidemiological investigators pursuing the role of β-carotene in anticarcinogenesis is whether the *all-trans*-β-carotene of commerce is the active agent or whether it serves merely as a reservoir for thermal, uncatalyzed generation of a cis congener(s) that functions as the true agent(s).

To obtain a more extensive picture of the quantitative effect of increasing the number of double bonds, efforts are underway to synthesize a semirigid model polyene of order 11 modified to include solubilizing *m*-hexyl groups in energetically innocuous positions. The 10th and 11th double bonds are expected to contribute so little to lowering the enthalpy of activation, even when strictly coplanar, that the *non-coplanar*, 10th and 11th double bonds of β-carotene are expected to contribute nothing to rearrangements about its central or near central double bonds.

Experimental Section

^{1}H-NMR spectra are recorded in $CDCl_3$ or C_6D_6 solution on Bruker AM-500 (500 MHz) and AM-300 (300 MHz) instruments. Quantitative ^{1}H-NMR spectra are measured allowing interpulse time delay (relaxation delay and saturation period) of at least five times the longest spin–lattice relaxation time (T_1) of the concerned protons. The spin–lattice relaxation times (T_1's) are measured by the inversion recovery method using degassed, vacuum-sealed solutions of the substance in C_6D_6. All chemical shifts are reported in ppm (δ) with respect to TMS. ^{13}C-NMR spectra are measured on Bruker AM-500 (125.8 MHz) or AM-300 (75.5 MHz) instruments. All chemical shifts are reported in ppm (δ) with respect to TMS. Infrared spectra (reported in cm^{-1}) are recorded on a Perkin-Elmer Model 337 grating spectrophotometer. Liquid samples are observed as thin films on a NaCl plate whereas solid samples are measured in KBr pellets or in a solution of CCl_4 or $CHCl_3$. UV–vis electronic spectra, measured on a Varian Cary 219 spectrophotometer, are reported as λ_{max} in nm.

Naphthalene-2,3-dicarboxylic Anhydride. Naphthalene-2,3-dicarboxylic anhydride[31] is prepared by refluxing naphthalene-2,3-dicarboxylic acid (25 g, 115.7 mmol) in acetic anhydride (65 mL) for 75 min. Anhydride precipitates with cooling and is isolated by vacuum sublimation (0.1 mm at 190–200 °C) as a colorless crystalline solid: mp 218 °C; 22.3 g, 97%; ^{1}H-NMR ($CDCl_3$, 300 MHz) 8.55 (s, 2 H, $H_{-1,4}$), 8.15 (dd, 2 H, J = 3.3 and 6.3 Hz, $H_{-5,8}$), 7.82 (dd, 2 H, J = 3.3 and 6.3 Hz, $H_{-6,7}$); ^{13}C-NMR ($CDCl_3$, 75.5 MHz) 163 (s), 136.1 (s), 130.4 (d), 130.5 (d), 127.8 (d), 126.0 (s); IR (CCl_4) 1863, 1860, 1780, 1345, 922, 890.

3-(4′-Methoxybenzoyl)naphthalene-2-carboxylic Acid. In a procedure analogous to that employed in the synthesis of 2-(4′-methoxybenzoyl)-benzoic acid,[32] anhydrous $AlCl_3$ (65 g, 0.486 mol) is added in portions over 0.5 h to a mechanically stirred suspension of the anhydride above (44.3 g, 0.2236 mol) in anisole (200 mL) with the temperature being allowed to rise to ca. 60 °C. The viscous, reddish reaction mass is then heated to 90 °C and stirred for 9 h. After being cooled to room temperature, the reaction complex is decomposed by cautious addition of 0.1 *N* HCl (200 mL). Excess anisole is removed by azeotropic distillation (with occasional addition of water to replenish the loss due to distillation). The resulting viscous residue, separated from a supernatant aqueous layer, is washed with 0.1 N HCl (2 × 100 mL) and dissolved in 10% aqueous NaOH (300 mL). The red solution is filtered through Celite and acidified with concentrated HCl to give a pasty precipitate, which is dissolved in 10% Na_2CO_3 solution (300 mL) and filtered. The filtrate is extracted with $CHCl_3$ (2 × 125 mL). The aqueous solution is then poured slowly under brisk stirring into concentrated HCl (150 mL) to obtain a colorless, crystalline precipitate, which is filtered, washed to neutrality with water, and oven-dried (53.5 g, 78.2%). The product so obtained is of reasonable purity (ca. 95–97% by NMR) and is used directly in the subsequent step. An analytical sample is obtained by recrystallisation from acetone: mp 239–240 °C; ^{1}H-NMR ($CDCl_3$, 300 MHz) 8.66 (s, 1 H, H_{-1}), 8.02 (d, 1 H, J = 8.5 Hz, H_{-8}), 7.86 (d, 1 H, J = 8.5 Hz, H_{-5}), 7.85 (s, 1 H, H_{-4}), 7.79 (d, 2 H, J = 8.6 Hz, $H_{-2',6'}$), 7.6–7.7 (m, 2 H, $H_{-6,7}$), 6.90 (d, 2 H, J = 8.6 Hz, $H_{-3',5'}$), 3.88 (s, 3 H, CH_3); ^{13}C-NMR (acetone-d_6, 125.8 MHz) 151.4, 132.4, 129.9, 129.1, 128.7, 128.5, 114.5, 55.9; IR (KBr) 3550–2700, 1670, 1595, 1460, 1290, 1255, 1020, 920, 890.

3-(4′-Methoxybenzyl)naphthalene-2-carboxylic Acid. In a procedure analogous to that employed by Iwata and Imoto[31] for the synthesis of 2-(4′-methoxybenzyl)benzoic acid, 3-(4′-methoxybenzoyl)naphthalene-2-carboxylic acid (53.8 g, 175.7 mmol) is dissolved in 500 mL of 20% aqueous ammonia, treated with a solution of $CuSO_4 \cdot 5H_2O$ (5.85 g, 23.4 mmol) in 90 mL of 20% aqueous ammonia, and heated to 60 °C. Activated Zn dust (107 g, 1.63 mol) is added cautiously (severe frothing!) in portions. The reaction mixture is stirred for 8 h at 100 °C, cooled to ca. 80 °C, treated with 50% aqueous NaOH (60 g, 0.75 mol), and stirred further for 1.5 h. The reaction mixture is filtered hot through Celite, which is washed with hot (ca. 60 °C) 5% aqueous NaOH (2 × 30 mL). The combined filtrates are added slowly with stirring to concentrated HCl (180 mL) to obtain a colorless, amorphous precipitate, which is filtered, washed to neutrality with water, and oven-dried (42 g; consisting of the desired acid and 3-(4′-methoxyphenyl)naphthalide in ca. 75:25 ratio in an overall yield of 82%).

This product (42 g, 143.5 mmol) is further reduced with Zn dust (80 g, 1.22 mol) and $CuSO_4 \cdot 5H_2O$ (4 g in 10 mL water) in 10% aqueous NaOH (500 mL) at 100 °C for 12 h. The reaction mixture is filtered hot (ca. 60 °C) and acidified with concentrated HCl to yield 3-(4′-hydroxylbenzyl)naphthalene-2-carboxylic acid as a colorless precipitate: 42.5 g, 95%; mp 219 °C; ^{1}H-NMR ($CDCl_3$, 500 MHz) 8.64 (s, 1 H, H_{-1}), 7.90 (d, 1 H, J = 7.9 Hz, H_{-8}), 7.76 (d, 1 H, J = 7.9 Hz, H_{-5}), 7.61 (s, 1 H, H_{-4}), 7.56 (t, 1 H, J = 7.9 Hz, H_{-6}), 7.48 (t, 1 H, J = 7.9 Hz, H_{-7}), 7.10 (d, 2 H, J = 8.3 Hz, $H_{-3',5'}$), 6.78 (br s, 2 H, $H_{-2',6'}$), 4.53 (s, 2 H, benzylic CH_2), 3.70 (br s, 2 H, OH and COOH); IR(KBr) 3640–3320, 3140–2700, 1690, 1510, 1465, 1290, 1250, 1180, 1030, 780, 750, 605.

A cooled (0 °C) suspension of 3-(4′-hydroxybenzyl)naphthalene-2-carboxylic acid (42.4 g, 152.3 mmol) in 200 mL of ether is treated with ethereal diazomethane (950 mL; ca. 0.36 M, 0.342 mol) and stirred for 1 h at 0 °C. Excess diazomethane is destroyed by addition of 2 mL of glacial acetic acid. The ethereal solution is washed with 10% Na_2CO_3 solution (100 mL) and water (2 × 100 mL), dried ($MgSO_4$), and then evaporated to dryness to obtain 2-carbomethoxy-3-(4′-methoxybenzyl)-naphthalene as a light yellowish oil: 41.7 g (89.4%); ^{1}H-NMR ($CDCl_3$, 500 MHz) 8.45 (s, 1 H, H_{-1}), 7.88 (d, 1 H, J = 8.1 Hz, H_{-8}), 7.77 (d, 1 H, J = 8.2 Hz, H_{-5}), 7.62 (s, 1 H, H_{-4}), 7.55 (dt, 1 H, J = 8.1 and 1.1 Hz, H_{-7}), 7.48 (dt, 1 H, J = 8.2 and 1.1 Hz, H_{-6}), 7.10 (d, 2 H, J = 8.6 Hz, $H_{-3',5'}$), 6.83 (d, 2 H, J = 8.6 Hz, $H_{-2',6'}$), 4.48 (s, 2 H, benzylic CH_2), 3.88 (s, 3 H, $COOCH_3$), 3.80 (s, 3 H, OCH_3); ^{13}C-NMR ($CDCl_3$, 125.8 MHz) 157.7, 138.1, 134.7, 132.8, 131.9, 131.0, 130.6, 129.8, 129.7, 128.4, 128.2, 128.0, 127.1, 126.0, 113.6, 55.0, 51.8, 38.9; IR (film) 3060, 3000, 2950, 2920, 2840, 1730, 1720, 1632, 1620, 1585, 1510, 1460, 1440, 1285, 1270, 1250, 1205, 1165, 1130, 1055, 1035, 950, 910, 825, 810, 792, 740.

This ester (41.5 g, 135.5 mmol) is hydrolyzed with 10% aqueous NaOH (100 mL) at 80–85 °C for 3 h. After being cooled, the resulting red solution is acidified by dropwise addition of 6 N HCl to obtain 3-(4′-methoxybenzyl)naphthalene-2-carboxylic acid as colorless crystals: 38.4 g (96.8%); mp 226 °C after recrystallization from acetone; ^{1}H-NMR ($CDCl_3$, 500 MHz) 8.63 (s, 1 H, H_{-1}), 7.92 (d, 1 H, J = 7.9 Hz, H_{-8}), 7.77 (d, 1 H, J = 7.9 Hz, H_{-5}), 7.62 (s, 1 H, H_{-4}), 7.57 (dt, 1 H, J = 7.9 and 1.2 Hz, H_{-6}), 7.51 (dt, 1 H, J = 7.9 and 1.2 Hz, H_{-7}), 7.12 (d, 2 H, J = 8.6 Hz, $H_{-3',5'}$), 6.83 (d, 2 H, J = 8.6 Hz, $H_{-2',6'}$), 4.52 (s, 2 H, benzylic CH_2), 3.78 (s, 3 H, OCH_3), 1.85 (br s, 1 H, COOH); ^{13}C-NMR (acetone-d_6, 125.8 MHz) 158.9, 139.8, 135.8, 134.1, 132.8, 132.7, 132.1, 131.1, 130.8, 130.6, 129.5, 129.0, 128.0, 127.1, 114.4, 55.4, 39.2; IR (KBr) 3620–3340, 3240–2720, 1688, 1514, 1180, 1150, 1035, 785, 750, 610.

3-Methoxy-5(12*H*)-naphthacenone. 3-(4′-Methoxybenzyl)-naphthalene-2-carboxylic acid (2 g, 6.84 mmol) is added in portions to cooled (0 °C) concentrated H_2SO_4 (15 mL) and stirred for 2.5 h. The reaction mixture is poured into ice-water (150 g) and extracted with CH_2Cl_2 (5 × 30) mL). The extract is washed with 5% aqueous $NaHCO_3$ (1 × 30 mL) and water (2 × 30 mL), dried ($MgSO_4$), and evaporated to dryness to give 930 mg (49.6%) of the desired naphthacenone as a light yellow solid. PPA-mediated cyclization does not proceed smoothly. A

(28) Tsukida, K.; Saiki, K.; Takai, T.; Koyama, Y. *J. Chromatogr.* **1982**, *245*, 359–364.
(29) Byers, J. *J. Org. Chem.* **1983**, *48*, 1515–1522.
(30) Sotiriou-Leventis, C.; Roth, W. R.; Doering, W. von E. *J. Chem. Soc.* In preparation.
(31) Lambert, P.; Martin, R. H. *Bull. Soc. Chim. Belg.* **1952**, *61*, 361–365.
(32) Iwata, M.; Imoto, S. *Bull. Chem. Soc. Jpn.* **1974**, *47*, 1687–1692.

better process involves intramolecular Friedel–Craft cyclization of the corresponding acid chloride.

3-(4′-Methoxybenzyl)naphthalene-2-carboxylic acid chloride is prepared by treating a hot (45–50 °C) suspension of 3-(4′-methoxybenzyl)naphthalene-2-carboxylic acid (38.2 g, 131 mmol) in $CHCl_3$ (400 mL) containing a catalytic (0.2 mL) amount of DMF with $SOCl_2$ (14.3 mL, 170 mmol), added dropwise over 20 min. The reaction mixture is stirred under reflux (62 °C) for about 3 h until gas evolution ceases, cooled to ambient temperature, filtered through Celite, and evaporated to dryness to give acid chloride as a waxy solid: 42.5 g, 95%; mp 28–32 °C; ^{1}H-NMR ($CDCl_3$, 500 MHz) 8.82 (s, 1 H, H_{-1}), 7.96 (d, 1 H, J = 8.2 Hz, H_{-8}), 7.77 (d, 1 H, J = 8.3 Hz, H_{-5}), 7.63 (dt, 1 H, J = 8.2 and 1.0 Hz, H_{-6}), 7.60 (s, 1 H, H_{-4}), 7.55 (dt, 1 H, J = 8.2 and 1.0 Hz, H_{-7}), 7.07 (d, 2 H, J = 8.5 Hz, $H_{-3',5'}$), 6.83 (d, 2 H, J = 8.5 Hz, $H_{-2',6'}$), 4.36 (s, 2 H, benzylic CH_2), 3.78 (s, 3 H, OCH_3); ^{13}C-NMR ($CDCl_3$, 125.8 MHz) 167.5, 158.1, 138.2, 137.0, 135.1, 131.7, 130.9, 130.8, 130.3, 130.1, 129.9, 129.4, 127.3, 126.9, 113.9, 55.2, 39.0; IR (film) 3040, 3000, 2968, 2950, 2920, 2840, 1760, 1630, 1615, 1590, 1510, 1452, 1245, 1175, 1030, 865, 820, 804, 755.

A solution of 3-(4′-methoxybenzyl)naphthalene-2-carboxylic acid chloride (40.3 g, 130 mmol) in CS_2/CH_2Cl_2 (260 mL/200 mL) is added slowly to a cooled (−20 °C) suspension of anhydrous $AlCl_3$ (43.5 g, 325 mmol) with the reaction mixture being maintained below −10 °C. The reddish yellow suspension is stirred for 12 h at ambient temperature. The reaction mixture is then diluted with CH_2Cl_2 (200 mL) and cooled to −10 °C. The reaction complex is decomposed by dropwise addition of water (200 mL), stirred for 0.5 h at ambient temperature, and filtered through Celite. The organic phase is separated, washed with 5% aqueous $NaHCO_3$ (150 mL) and water (2 × 200 mL), dried ($MgSO_4$), and evaporated to dryness to yield 35.0 g (98.2%) of the desired naphthacenone as a light yellow crystalline solid: mp 168–169 °C; ^{1}H-NMR ($CDCl_3$, 500 MHz) 8.90 (s, 1 H, H_{-6}), 8.02 (d, 1 H, J = 8.3 Hz, H_{-7}), 7.88–7.78 (m, 3 H, $H_{-4,10,11}$), 7.58 (dt, 1 H, J = 8.2 and 1.2 Hz, H_{-9}), 7.50 (dt, 1 H, J = 8.2 and 1.2 Hz, H_{-8}), 7.37 (d, 1 H, J = 8.5 Hz, H_{-1}), 7.19 (dd, 1 H, J = 8.5 and 2.8 Hz, H_{-2}), 4.39 (s, 2 H, $H_{-12,12'}$), 3.91 (s, 3 H, OCH_3); ^{13}C-NMR ($CDCl_3$, 125.8 MHz) 184.5, 158.6, 135.5, 135.3, 133.4, 133.0, 131.7, 129.7, 129.65, 129.6, 129.0, 128.4, 127.0, 126.8, 126.0, 122.0, 109.1, 55.5, 31.5; IR (KBr): 3050, 3010, 2940, 2740, 1658, 1612, 1495, 1310, 1280, 1240, 780.

5,12-Dihydro-3-methoxynaphthacen-5-ol. A stirred mixture of 3-methoxynaphthacen-5(12*H*)-one (34.5 g, 126 mmol), toluene (700 mL), activated Zn dust (130 g; 1.98 mol), and 2 N aqueous NaOH (2 L) is refluxed for 40 h. After the solution is cooled to ambient temperature, the organic phase is separated, washed with water (3 × 200 mL), and evaporated to dryness in a rotary evaporator to yield 5,12-dihydro-3-methoxynaphthacen-5-ol as a light-yellow solid: 32.0 g, 92.2%; ^{1}H-NMR ($CDCl_3$, 500 MHz) 8.07 (s, 1 H, H_{-6}), 7.88 (d, 1 H, J = 8.8 Hz, H_{-7}), 7.82 (d, 1 H, J = 8.8 Hz, H_{-10}), 7.77 (s, 1 H, H_{-11}), 7.51–7.41 (m, 2 H, $H_{-8,9}$), 7.27–7.22 (m, 2 H, $H_{-1,4}$), 6.84 (dd, 1 H, J = 8.3 and 2.5 Hz, H_{-2}), 5.74 (br s, 1 H, H_{-5}), 4.20 (d, 1 H, J = 17.4 Hz, H_{-12}), 3.98 (d, 1 H, J = 17.4 Hz, $H_{-12'}$), 3.85 (s, 3 H, OCH_3), 2.20 (br s, 1 H, OH); ^{13}C-NMR ($CDCl_3$, 125.8 MHz) 158.6, 140.3, 137.8, 134.3, 132.4, 131.9, 128.4, 128.1, 127.8, 127.2, 126.1, 125.6, 125.5, 124.2, 113.2, 111.0, 71.0, 55.5, 34.6; IR (KBr) 3600–3120, 3080, 2960, 1625, 1520, 1300, 1180, 1040, 805, 760.

2-Methoxynaphthacene (6). 5,12-Dihydro-3-methoxynaphthacen-5-ol (31.8 g; 115 mol) is suspended in $CHCl_3$ (200 mL), sonicated for 20 min, acidified with 0.2 mL of trifluoroacetic acid, and stirred overnight at room temperature. The bright orange precipitate is filtered, washed with CH_2Cl_2, and dried (23.8 g). The chloroform filtrate is washed with 5% aqueous $NaHCO_3$ (20 mL) and water (2 × 100 mL), dried ($MgSO_4$), and evaporated to dryness. The residue is recrystallized from toluene to yield an additional 2.4 g of 2-methoxynaphthacene: total 26.2 g, 88.2%; mp >300 °C (lit.[33] mp 324–7 °C); ^{1}H-NMR ($CDCl_3$, 500 MHz) 8.63 (s, 1 H, H_{-5}), 8.58 (s, 2 H, $H_{-6,11}$), 7.99–7.97 (m, 2 H, $H_{-7,10}$), 7.89 (d, 1 H, J = 9.3 Hz, H_{-4}), 7.40–7.35 (m, 2 H, $H_{-8,9}$), 7.16 (d, 1 H, J = 2.2 Hz, H_{-1}), 7.11 (dd, 1 H, J = 9.3 and 2.2 Hz, H_{-3}), 3.99 (s, 3 H, OCH_3); ^{13}C-NMR ($CDCl_3$, 125.8 MHz) 129.6, 128.2, 128.1, 126.7, 126.6, 123.6, 123.5, 122.5, 122.4, 122.0, 112.8, 110.3, 106.5, 79.2, 55.5; IR (KBr) 1648, 1635, 1580, 1300, 1240, 1185, 1038, 910, 815, 750.

1,4,5,6,7,10,11,12-Octahydro-2-methoxynaphthacene. Birch reduction of 2-methoxynaphthacene (6) under normal conditions[34] leads to a mixture of products consisting mostly of 5,6,11,12-tetrahydromethoxynaphthacene. To obtain the desired octahydro derivative, a suspension of 6 (10.4 g, 40 mmol) in THF (120 mL) is added to 850 mL of dry liquid ammonia kept at −78 °C (acetone/dry ice). Lithium wire (7.3 g, 1.03 mol) is added in small pieces over 1 h to obtain a dark blue solution. The cooling bath is removed and the reaction mixture is allowed to come to reflux temperature (ca. −40 °C). A mixture of diispropylamine (90 mL) and THF (90 mL) followed by a mixture of ethanol (60 mL) and THf (60 mL) is added dropwise over a period of 8 h. The reaction mixture is stirred overnight while ammonia evaporates slowly. Water (150 mL) is added cautiously, followed by CH_2Cl_2 (400 mL). After the mixture is stirred for 0.5 h, the organic phase is separated and washed with water (3×150 mL), dried ($MgSO_4$), and evaporated to dryness to yield a colorless solid, which is used without purification in the next step: 10.5 g; 86% of ca. 88% purity by NMR. An analytical sample is obtained by three recrystallizations from ethanol/THF (1:1): mp 145–6 °C; ^{1}H-NMR ($CDCl_3$, 500 MHz) 5.72 (s, 2 H, $H_{-8,9}$), 4.62 (t, 1 H, J = 3.3 Hz, H_{-3}), 3.56 (s, 3 H, OCH_3), 2.74–2.63 (m, 2 H, $H_{-1,1'}$), 2.63–2.57 (m, 2 H, $H_{-4,4'}$), 2.55 (s, 4 H, $H_{-5,5',12,12'}$), 2.46 (s, 4 H, $H_{-6,6',11,11'}$), 2.43 (s, 4 H, $H_{-7,7',10,10'}$); ^{13}C-NMR ($CDCl_3$, 125.8 MHz) 152.9, 124.5, 124.8, 124.4, 123.6, 123.45, 123.4, 123.35, 123.1, 122.6, 90.5, 53.8, 35.6, 35.55, 35.5, 35.0, 32.8, 30.9, 30.5; IR (solid film) 2880, 2840, 2820, 1670, 1220, 780, 660.

4,4a,5,5a,6,6a,7,8-Octahydronaphthacen-2(3*H*)-one 5. A mixture of 1,4,5,6,7,10,11,12-octahydro-2-methoxynaphthacene (10.2 g, 34 mmol, 88% purity), THF (500 mL), and perchloric acid (40%, 200 mL) is stirred at ambient temperature for 20 h. The mixture is diluted with water (400 mL) and extracted with $CHCl_3$ (300 mL and 2 × 100 mL). The combined organic extracts are washed with 5% aqueous $NaHCO_3$ solution (2 × 150 mL) and water (2 × 150 mL), dried ($MgSO_4$), and evaporated to dryness to give 10.8 g of crude product, which is recrystallized from toluene to obtain 4.4 g of dark yellow crystals (purity ca. 90% by NMR). The crude material recovered from the mother liquor is partially purified by flash chromatography on silica gel (eluant: hexane/ethyl acetate (1:1); R_f = 0.35). The reaction product is repeatedly recrystallized from toluene to yield 4.8 g (56%) of the desired product as a yellow crystalline solid; mp 224–5 °C; ^{1}H-NMR ($CDCl_3$, 500 MHz) 6.13 (d, 1 H, J = 9.7 Hz, H_{-10}), 6.10 (s + m, 2 H, $H_{-9,11}$), 5.94 (s, 1 H, H_{-12}), 5.76 (s, 1 H, H_{-1}), 2.61–2.49 (m, 2 H, $H_{-5a,6a}$), 2.49–2.35 (m, 3 H, $H_{-3,3',4a}$), 2.32–2.18 (m, 2 H, $H_{-8,8'}$), 2.10–2.01 (m, 1 H, H_{-4}), 1.96–1.80 (m, 3 H, $H_{-5,6,7}$), 1.77–1.64 (m, 1 H, $H_{-4'}$), 1.38–1.28 (m, 1 H, $H_{-7'}$), 1.28–1.19 (m, 1 H, $H_{-6'}$), 1.19–1.10 (m, 1 H, $H_{-5'}$); ^{13}C-NMR ($CDCl_3$, 125.8 MHz) 199.7, 159.9, 149.9, 145.3, 133.6, 128.7, 124.4, 123.9, 122.6, 37.9, 37.3, 36.9, 36.2, 35.9, 35.7, 30.2, 29.7, 26.0; IR (KBr) 2920, 2860, 1650, 1590, 1330, 1250, 1200, 900.

4,4′,4a,5,5′,5a,5a′,6,6a,6a′,7,7′,8,8′-Hexadecahydro-2,2′-bi-(3*H*)-naphthacenylidene (4). $TiCl_4$ (2 mL, 3.44 g; 18 mmol) is added dropwise with a syringe to cooled (ca. −15 °C), freshly distilled THF (80 mL) under nitrogen. Activated Zn dust (2.8 g, 43 mmol) is added in portions to the yellow suspension as the reaction mixture warms to ambient temperature. The reaction mixture is heated to reflux. Pyridine (1.6 mL) is added by syringe and reflux is maintained for 0.25 h to obtain a fine, black suspension of "Titanium Reagent".[1] A solution of tetraenone 5 (400 mg; 1.6 mmol) in THF (120 mL) is added dropwise (addition time ca. 5 min), and the reaction mixture is further refluxed for 0.25 h, cooled to room temperature, and poured into an agitated mixture of water (250 mL) and $CHCl_3$ (350 mL), which has been thoroughly purged with argon and saturated with CO_2. The orange organic phase is separated, washed with CO_2-saturated water (2 × 150 mL), dried ($MgSO_4$), and evaporated to dryness in a rotary evaporator to give 320 mg of crude product as a dark orange solid. The solid is treated with a (1:1) mixture of acetone/benzene (300 mL), sonicated for 0.5 h, and filtered. Cooling the filtrate to ca. −8 °C affords 95 mg (0.2 mmol, 25%) of {4-1-4} nonaene 4 as a dark red solid: mp >300 °C in a sealed tube; syn/anti ratio, ca. 85:15 by NMR; ^{1}H-NMR ($CDCl_3$, 500 MHz) 6.62 (s, 2 H, $H_{c\alpha/\beta s}$, H_{-1}), 6.59 (s, 2 H, $H_{\beta s/c\alpha}$, H_{-1}), 6.39 (s, 2 H, $H_{c\alpha/\beta a}$, H_{-1}), 6.36 (s, 2 H, $H_{\beta a/c\alpha}$, H_{-1}), 6.13 (d, 2 H, H_{s+a}, J = 9.7 Hz, H_{-10}), 6.01 (s, 2 H, H_{s+a}, H_{-12}), 5.91 (s, 2 H, H_{s+a}, H_{-11}), 5.88–5.80 (m, 2 H, H_{s+a}, H_{-9}), 2.95–2.85 (pseudo t, 2 H, H_a, J = 15.2 Hz, H_{-3}), 2.79 (d, 2 H, $H_{c\alpha/\beta s}$, J = 15.3 Hz, H_{-3}), 2.58 (d, 2 H, $H_{\beta s/c\alpha}$, H_{-3}), 2.50–1.80 (m, 18 H, H_{s+a}), 1.4–1.2 (m, 6 H, H_{s+a}), 1.18–1.0 (m, 4 H, H_{s+a}). The α and β stereoisomers of the syn (s) and anti (a) forms are found in equal proportion. The syn/anti ratio is ca. 90:10. This sample is used directly in kinetic studies. The crystalline compound polymerizes slowly even under an inert atmosphere at low temperature (−20 °C) but can be freed of polymer by filtering a $CHCl_3$ solution through silica gel.

2-Cyclohex-2′-en-1′-ylidene-2,3,4,4a,5,5a,6,6a,7,8-decahydronaphthacene [{4-1-1} Hexaene]. To a refluxing suspension of "Titanium Reagent" (prepared in the way outlined above from 6.25 mL of $TiCl_4$ (56.8 mmol), 8.75 g of activated Zn dust (133.6 mmol), 150 mL of freshly distilled THF, and 5.1 mL of pyridine) is added a solution of tetraenone 5 (255 mg, 1 mmol) and 2-cyclohexen-1-one (385 mg, 4 mmol) in THF (50 mL). The reaction mixture is refluxed further for 0.25 h, cooled to ambient temperature, and added to an agitated mixture

(33) Smith, D. C. C. *J. Chem. Soc.* **1962**, 673–674.
(34) Birch, A. J.; Murray, A. R.; Smith, H. J. *J. Chem. Soc.* **1951**, 1945–1950.

of CO_2-saturated water (300 mL) and CH_2Cl_2 (250 mL). The aqueous phase is extracted with CH_2Cl_2 (2 × 100 mL). The organic phase is washed with CO_2-saturated water (2 × 150 mL), dried ($MgSO_4$), and evaporated to dryness to obtain a crude mixture of {1-1-1} triene $\mathbf{1}_{1.1.1}$ (see Table III) and {4-1-1} hexaene as a reddish yellow solid: 600 mg, ca. 80%. The crude product is triturated with hexane (10 mL), sonicated, and filtered. The residue is again treated with hexane (10 mL) in the same manner. The residue (ca. 200 mg) is recrystallized from acetone to yield {4-1-1} hexaene as an orange, crystalline solid: 120 mg, 38%; syn/anti ratio ca. 52:48 by NMR; ^{1}H-NMR ($CDCl_3$, 500 MHz) 6.72 (d, 1 H, H_s, J = 10.2 Hz, $H_{-2'}$), 6.51 (d, 1 H, H_a, J = 10.2 Hz, $H_{-2'}$), 6.50 (s, 1 H, H_s, H_{-1}), 6.35 (s, 1 H, H_a, H_{-1}), 6.11 (d, 1 H, H_{s+a}, J = 9.6 Hz, H_{-10}), 5.98 (s, 1 H, H_{s+a}, H_{-12}), 5.96 (s, 1 H, H_{a+s}, H_{-12}), 5.90 (s, 1 H, H_{s+a}, H_{-11}), 5.88–5.76 (m, 2 H, H_{s+a}, $H_{-9,3'}$), 2.85 (d, 1 H, H_a, J = 14.6 Hz), 2.68 (d, 1 H, H_s, J = 14.6 Hz), 2.58–1.60 (m, 16 H, H_{s+a}), 1.38–1.15 (m, 2 H, H_{s+a}), 1.15–1.00 (m, 2 H, H_{s+a}); ^{1}H-NMR (C_6D_6, 500 MHz) 6.92 (d, 1 H, H_s, J = 10.2 Hz, $H_{-2'}$), 6.74 (s, 1 H, H_s, H_{-1}), 6.67 (d, 1 H, H_a, J = 10.1 Hz, $H_{-2'}$), 6.54 (s, 1 H, H_a, H_{-1}), 6.21 (d, 1 H, H_{s+a}, H_{-10}), 6.12 (s, 1 H, H_a, H_{-12}), 6.08 (s, 1 H, H_s, H_{-12}), 6.04 (s, 1 H, H_{s+a}, H_{-11}), 5.86–5.70 (m, 2 H, H_{s+a}, $H_{-9,6'}$), 2.87 (d, 1 H, H_a, J = 14.8 Hz), 2.61 (d, 1 H, H_s, J = 14.8 Hz), 2.48–0.80 (m, 20 H, H_{s+a}).

Repeated recrystallization from different solvents (e.g., acetone, hexane, THF, toluene, and cyclohexane) does not lead to enrichment in either of the isomers. Partial separation of the syn and anti isomers can be achieved through HPLC (column, 4.5 × 250 mm Zorbax ODS; eluant, acetone/acetonitrile/water (85:10:5); flow, 1 mL/min.; detection, UV-vis (405 nm); retention time, 12 and 12.5 min). However, attempts to separate these two isomers preparatively have not succeeded. As no enrichment in either of the isomers (syn/anti) could be achieved, no kinetic investigation could be undertaken with this polyene.

2-(2′,3′,4′,4a′,5′,6′-Hexahydro-2′-naphthylidene)-2,3,4,4a,5,5a,6,-6a,7,8-decahydronaphthacene [{4-1-2] Heptaene $\mathbf{7}_{4.1.2}$]. To a refluxing suspension of "Titanium Reagent" (prepared from $TiCl_4$ (6.25 mL, 56 mmol), activated Zn dust (8.75 g, 133.6 mmol), 150 mL of freshly distilled THF, and 5.1 mL of pyridine) is added a solution of tetraenone **5** (255 mg, 1 mmol) and 4,4a,5,6-tetrahydro-2(3*H*)-naphthalenone[1] (592 mg, 4 mmol) in THF (50 mL). The reaction mixture is refluxed for 0.25 h, cooled to room temperature, and added to a stirred mixture of CO_2-saturated water (300 mL) and $CHCl_3$ (150 mL). The aqueous phase is extracted with $CHCl_3$ (2 × 100 mL). The organic phase is washed with CO_2-saturated water (2 × 150 mL), dried ($MgSO_4$), and evaporated to dryness to give a crude mixture of {2-1-2} pentaene $\mathbf{2}_{2.1.2}$ and {4-1-2} heptaene $\mathbf{7}_{4.1.2}$ as an orange solid (ca. 700 mg). This residue is treated with 120 mL THF (freshly distilled) and heated to reflux under nitrogen for 2 h. The resulting orange solution is cooled (−6 °C). *anti*-α/β-$\mathbf{7}_{4.1.2}$ (α and β stereoisomers is ca. 55:45 ratio) precipitates as orange crystals (mp >300 °C). The mother liquor is concentrated to ca. 80 mL and heated again to reflux for 2 h. Upon cooling, a second crop of *anti*-α/β-$\mathbf{7}_{4.1.2}$ (the isomer used in kinetic studies) is obtained. This procedure is repeated to obtain a third crop. The combined yield is 150 mg, 40.8%. An equilibrium mixture of syn(α/β) and anti(α/β) isomers is obtained by heating (110 °C, 3.5 h) a degassed C_6D_6 solution of the anti(α/β) isomer sealed in an NMR tube: ^{1}H-NMR (anti α/β isomer, $CDCl_3$, 500 MHz) 6.38 (s, 1 H, $H_{\alpha a}$, H_{-1}), 6.35 (s, 1 H, $H_{\beta a}$, H_{-1}), 6.33 (s, 1 H, $H_{\alpha a}$, $H_{-1'}$), 6.29 (s, 1 H, $H_{\beta a}$, $H_{-1'}$), 6.13 (pseudo t, 2 H, $H_{\alpha\beta a}$, J = 9.,7 Hz, $H_{-10,8'}$), 5.98 (s, 1 H, $H_{\alpha\beta a}$, H_{-11}), 5.91 (s, 1 H, $H_{\alpha\beta a}$, H_{-12}), 5.88–5.79 (m, 2 H, $H_{\alpha\beta a}$, $H_{-9,7'}$), 2.97–2.84 (m, 2 H, $H_{\alpha\beta a}$), 2.60–2.30 (m, 10 H, $H_{\alpha\beta a}$), 2.00–1.80 (m, 6 H, $H_{\alpha\beta a}$), 1.37–1.22 (m, 4 H, $H_{\alpha\beta a}$), 1.16–1.01 (m, 2 H, $H_{\alpha\beta a}$); ^{1}H-NMR (syn/anti α/β isomers; $CDCl_3$, 500 MHz) 6.58 (s, 1 H, $H_{\alpha s}$, H_{-1}), 6.56 (s, 1 H, $H_{\beta s}$, H_{-1}), 6.54 (s, 1 H, $H_{\alpha s}$, $H_{-1'}$), 6.51 (s, 1 H, $H_{\beta s}$, $H_{-1'}$), 6.38 (s, 1 H, $H_{\alpha a}$, H_{-1}), 6.35 (s, 1 H, $H_{\beta a}$, H_{-1}), 6.33 (s, 1 H, $H_{\alpha a}$, $H_{-1'}$), 6.29 (s, 1 H, $H_{\beta a}$, $H_{-1'}$), 6.15–6.11 (m, 2 H, $H_{\alpha\beta s+\alpha\beta a}$, $H_{-10,8'}$), 5.98 (s, 1 H, $H_{\alpha\beta s+\alpha\beta a}$, H_{-11}), 5.91 (s, 1 H, $H_{\alpha\beta s+\alpha\beta a}$, H_{-12}), 5.88–5.79 (m, 2 H, $H_{\alpha\beta s+\alpha\beta a}$, $H_{-9,7'}$), 2.97–2.84 (m, 2 H, $H_{\alpha\beta s+\alpha\beta a}$), 2.60–2.30 (m, 10 H, $H_{\alpha\beta s+\alpha\beta a}$), 2.00–1.80 (m, 6 H, $H_{\alpha\beta s+\alpha\beta a}$), 1.37–1.22 (m, 4 H, $H_{\alpha\beta s+\alpha\beta a}$), 1.16–1.01 (m, 2 H, $H_{\alpha\beta s+\alpha\beta a}$); ^{1}H-NMR (syn/anti α/β isomers; C_6D_6, 500 MHz) 6.86 (br s, 2 H, $H_{\alpha s}$, $H_{-1,1'}$), 6.83 (br s, 2 H, $H_{\beta s}$, $H_{-1,1'}$), 6.59 (s, 1 H, $H_{\alpha a}$, H_{-1}), 6.56 (s, 1 H, $H_{\beta a}$, H_{-1}), 6.54 (s, 1 H, $H_{\alpha a}$, $H_{-1'}$), 6.50 (s, 1 H, $H_{\beta a}$, $H_{-1'}$), 6.34–6.26 (m, 1 H, $H_{\alpha\beta s+\alpha\beta a}$, $H_{-8'}$), 6.22 (d, 1 H, $H_{\alpha\beta s+\alpha\beta a}$, J = 9.6 Hz, H_{-10}), 6.15 (s, 1 H, $H_{\alpha\beta a}$, H_{-12}), 6.08 (s, 1 H, $H_{\alpha\beta s}$, H_{-12}), 6.05 (s, 1 H, $H_{\alpha\beta s+\alpha\beta a}$, H_{-11}), 5.82–5.72 (m, 2 H, $H_{\alpha\beta s+\alpha\beta a}$, $H_{-9,7'}$), 2.97–2.84 (m, 2 H, $H_{\alpha\beta s+\alpha\beta a}$), 2.40–1.98 (m, 10 H, $H_{\alpha\beta s+\alpha\beta a}$), 1.80–1.70 (m, 2 H, $H_{\alpha\beta s+\alpha\beta a}$), 1.70–1.55 (m, 4 H, $H_{\alpha\beta s+\alpha\beta a}$), 1.40–1.20 (m, 4 H, $H_{\alpha\beta s+\alpha\beta a}$), 1.16–1.00 (m, 2 H, $H_{\alpha\beta s+\alpha\beta a}$); IR ($CHCl_3$) 2960, 2930, 1640, 1460, 1380, 1332, 11262, 1205, 920, 765; UV (CH_2Cl_2) 392 (103 680), 413 (106 920), 442 (95 730).

Kinetics of Syn–Anti Isomerization of {4-1-4} Nonaene, *anti*-$\mathbf{4}_{4.1.4}$. A saturated solution of nonaene $\mathbf{4}_{4.1.4}$ is prepared by sonicating ca. 1–2 mg of crystalline solid (syn/anti ratio ca. 85:15) in 1 mL of C_6D_6 (Cambridge Isotope Laboratory, 100%) under an argon atmosphere for ca. 5 min. The solution is filtered through a 0.4-μm Nylon filter to remove undissolved solid. An NMR tube (no. 528, Pyrex glass, elongated) is thoroughly cleaned by soaking in 20% ammonia (24 h) and washing with distilled water and analytical grade acetone. Approximately 0.5 mL of this nonaene solution is placed in the dried NMR tube, degassed by three vacuum, freeze–thaw cycles, and sealed under vacuum (10^{-3} mmHg).

The reaction mixture is analyzed on a Bruker AM-500 (500 MHz) NMR spectrometer by using H_{-1} signals at 6.95 (α-syn), 6.93 (β-syn), 6.63 (α-anti), and 6.60 (β-anti) employing a pulse interval of 3.9 s. Generally, accumulation of 1600–2000 scans (accumulation time ca. 2 h) is required to achieve reasonable signal-to-noise ratio. The syn/anti ratio is determined from the ratio of the intensities of the sum of the signals at 6.95 and 6.93 to the sum of the signals at 6.63 and 6.60 (initial syn/anti ratio, 83.5:16.5).

The sealed NMR tube is heated in the vapor of refluxing dioxane (101 °C) for 0.5 h. Minute amounts of product precipitate. Because no satisfactory NMR spectra can be recorded even after very prolonged accumulation, no further kinetic investigation of the anti–syn isomerization of {4-1-4} nonaene $\mathbf{4}_{4.1.4}$ was undertaken.

Kinetics of the Syn–Anti Isomerization of Heptaene $\mathbf{7}_{4.1.2}$. A saturated solution of $\mathbf{7}_{4.1.2}$ is prepared by sonicating ca. 1–2 mg of crystalline, predominantly anti isomer in 1 mL of C_6D_6 (Cambridge Isotope Laboratory, 100%) under an argon atmosphere for ca. 5 min. The solution is filtered through a 0.45-μm Nylon filter to remove undissolved solid. Approximately 0.5 mL of this solution is placed in a dried NMR tube (prepared as described in the previous experiment), degassed by three vacuum, freeze–thaw cycles, and sealed under vacuum (10^{-3} mmHg). After the zero-point NMR reading is taken, the sealed NMR tube is heated in a constant temperature vapor bath[1] for the noted periods of time. The extent of conversion to syn isomer is determined periodically by NMR spectroscopy. The same NMR tube is then heated further at the same temperature for additional periods until a state near to equilibrium is reached (total run time ca. 9–10 half-lives). The temperature of the heating bath is measured by a digital thermometer (Digisense Model No. 8528-30, Cole Parmer Instrument Co.) employing a J-type thermocouple as temperature sensor (error ±0.2 °C). Temperature is recorded immediately before and immediately after each heating period. However, for longer runs, temperature is recorded every 12–18 h without disturbing the kinetic experiment. The temperature of the vapor bath has been observed to fluctuate within tolerable limits (±0.35 °C), depending upon barometric pressure and humidity. Temperature of each heating period is taken as the mean of the temperatures recorded before and after the kinetic run. The mean of the temperatures of the individual intervals gives the average temperature of the kinetic experiment.

The compounds used in the constant temperature vapor bath for the different kinetic experiments along with their boiling point range follow: dioxane (100.8–101.5 °C), toluene (111.0–111.4 °C), trichloroethylene (87.1–87.8 °C), and ethyl acetate (77.0–77.4 °C).

Syn/anti (product/educt) ratios are determined by analysis on a Bruker AM-500 (500 MHz) NMR spectrometer directly from the ratio of the sums of the intensities of the signals at 6.86 and 6.83 ppm (syn $\alpha\beta$; T_1 = ca. 0.72 s) to those at 6.59, 6.56, 6.54, and 6.50 ppm (anti $\alpha\beta$; T_1 = ca. 0.72 s), employing an interpulse delay of ca. 3.8 s (RD = 0.53 s, AQ = 3.28 s). Generally, accumulation of 1600–2000 scans (accumulation time ca. 2 h) is required to achieve reasonable signal-to-noise ratios. As the α and β stereoisomers of the syn and anti isomers overlap slightly, no attempt has been made to integrate the signals separately. Results are given in Table II. Reaction rates and equilibrium constants at each of the individual temperatures are optimized simultaneously by the nonlinear least-squares method to fit the reversible first-order kinetic equation to the observed data.[1] The activation parameters are calculated from the observed rate and equilibrium constants at the different experimental temperatures.

Acknowledgment. This investigation has been supported by the PHS (Grant No. 1 RO 1 CA 41325, awarded by the National Cancer Institute, DHHS) and by the National Science Foundation (Grant No CHE-88 16186).