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Hammett ρ^+ Values as Kinetic Evidence for the Concerted Biomimetic Bicyclization Mechanism

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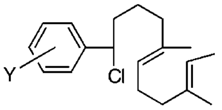
Chlorides **1** (1-aryl-1-chloro-5,9-dimethyl-5,9-undecadienes) with various phenyl substituents were prepared (Y = *p*-OCH_3, *p*-CH_3, H, *p*-Br, and *m*-Br), and solvolysis rates were measured in 80% (v/v) aqueous ethanol and in 97% (wt/wt) aqueous 2,2,2-trifluoroethanol. The Hammett ρ^+ values obtained are −1.5 and −1.8, respectively, indicating the concerted bicyclization. Comparison with ρ^+ values that correspond to solvolysis of the benzylic squalene derivatives **3** ($\rho^+ = -1.8$ and −1.6 in the same solvents) leads to the conclusion of the concerted bicyclization in **3** and may also suggest concerted bicyclization under biomimetic conditions in the natural precursor, 2,3-epoxysqualene, as well.

Introduction

The question of the concertedness in biomimetic policyclization reactions has been discussed for more than three decades.[1−3] Of the two pioneers in this field, Johnson[4] considered that the concerted mechanism is possible, while van Tamelen[5] stated that only monocyclization might be a concerted process and that further cyclization is stepwise; i.e., the reaction proceeds by way of mono-, bi-, and tricyclic carbocationic intermediates, which are separated by energy barriers. van Tamelen also demonstrated that biomimetic conditions can be used to rationalize the formation of the first three rings, since the epoxide ring opening of the 2,3-epoxysqualene, initiated with Lewis acid, produced tricyclic products.[6] Recently, several papers appeared generally supporting the stepwise rings closures.[7] Bicyclic and tricyclic carbocation intermediates were trapped in those studies.[7b,c] However, monocyclic products were not observed; thus, the concerted bicyclization cannot be ruled out. In this paper, we would like to show that concerted biomimetic bicyclization mechanism is operative in solvolytic conditions, not only for model compounds, but also for a squalene derivative.

The cases in which concerted bicyclization was established with great certainty in solvolysis were the benzylic chloride **1** with Y = H, and the tertiary chloride **2**, both systems having the same side chain, with two trans-trisubstituted double bonds positioned to facilitate the closure of two six-membered rings, as in the natural epoxysqualene.[8,9] The values of the activation parameters obtained in ethanolysis of chloride **1** ($\Delta H^{\ddagger} = 36 \pm 4$ kJ mol^{-1}, $\Delta S^{\ddagger} = -195 \pm 12$ J K^{-1} mol^{-1})[8] and the activation volumes (-24.0 ± 0.5 cm^3 mol^{-1})[10] were all consistent only with the extended π-participation mechanism. The most significant result that strongly supports the concerted bicyclization in the case of the tertiary chloride **2** was the secondary β-deuterium kinetic isotope effect (KIE), which was drastically reduced.[9] Thus, in the ethanolysis of the saturated analogue of **2** the KIE was 1.80 ± 0.03. For the corresponding tertiary chloride with one double bond the effect was considerably reduced ($k_H/k_D = 1.37 \pm 0.03$), suggesting a concerted monocyclization. However, under the same conditions, chloride **2** solvolyzed without a significant secondary β-deuterium KIE ($k_H/k_D = 1.01 \pm 0.04$), indicating extended π-participation of both double bonds in the rate-determining step.



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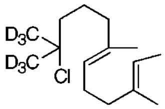

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Y = *p*-OCH_3, *p*-CH_3, H, *p*-Br, *m*-Br

We considered that evaluating the reaction constant (Hammett ρ^+)[11] for solvolysis of the benzylic system **1** would not only provide an additional test for concerted bicyclization but, even more important, that value could be used as a reference in testing for concerted bicycliza-

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[†] Deceased on October 23, 1997.

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(2) For reviews on polyene cyclizations, see: (a) Taylor, S. K. *Org. Prep. Proced. Int.* **1992**, *24*, 245−284. (b) Sutherland, J. K. In *Compehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon Press: New York, 1991; Vol. 3, pp 341−377. (c) Bartlett, P. A. In *Asymmetric Synthesis*; Morrison, J. D., Ed.; Academic Press: New York, 1984; Vol. 3, pp 341−409.

(3) For a review on kinetic approach to the mechanism of cationic polyolefinic cyclization, see: Borčić, S.; Kronja, O.; Humski, K. *Croat. Chem. Acta* **1994**, *67*, 171−188 and references therein.

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(5) (a) van Tamelen, E. E. *J. Am. Chem. Soc.* **1982**, *104*, 6480−6481 and references therein. (b) van Tamelen, E. E. *Pure Appl. Chem.* **1981**, *53*, 1259−1270.

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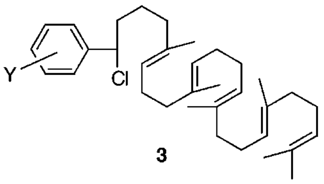
Table 1. Solvolysis Rate Constants and Activation Parameters for 1-Aryl-1-chloro-5,9-dimethyl-5,9-undecadienes 1 at 25 °C

compd[a]	solvent[b]	$k/$ 10^{-4} s^{-1} [c]	$\Delta H^{\ddagger}/$ kJ mol^{-1} [d]	$-\Delta S^{\ddagger}/$ J K^{-1} mol^{-1} [d]
1-*p*-OCH$_3$	80E	25.7	46 ± 4	142 ± 13
	97T	119 ± 2		
1-*p*-CH$_3$	80E	5.10	46 ± 4	151 ± 13
	97T	19.3 ± 0.8	54 ± 4	108 ± 13
1-H	80E	2.06	43 ± 3	172 ± 8
	97T	4.61 ± 0.03	62 ± 2	100 ± 8
1-*p*-Br	80E	1.22	32 ± 3	213 ± 8
	97T	2.61	44.4 ± 0.2	164.4 ± 0.4
1-*m*-Br	80E	0.46	42 ± 4	184 ± 17
	97T	1.05[e]	50[f]	154[f]

[a] Substituents on the phenyl ring. [b] 80E is 80% (v/v) aqueous ethanol, and 97T is 97% (wt/wt) aqueous 2,2,2-trifluoroethanol. [c] Uncertainties are standard errors. The rate constants without standard errors are extrapolated values from the data determined at three temperatures. [d] Uncertainties are standard deviations. [e] Extrapolated value from the data determined at two temperatures. [f] Calculated from the data determined at two temperatures.

tion in other systems, where doubt about a mechanism exists, such as in the solvolysis of **3** and **4**. The importance of the latter structures comes from their structural relation to the natural precursor of the steroids, squalene.



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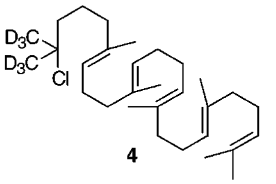

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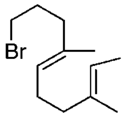
Y = *p*-OCH$_3$, *p*-CH$_3$, H, *p*-Br, *m*-Br

Results and Discussion

To obtain the ρ^+ values for the benzylic system **1**, a series of benzylic chlorides **1** were prepared (Y = *p*-OCH$_3$, *p*-CH$_3$, H, *p*-Br, and *m*-Br). The parent carbinols of **1** were obtained using the Barbier addition of bromide **5** (prepared according to the earlier presented procedure[10,12]) to the corresponding benzaldehydes in the presence of lithium. The alcohols were converted to chlorides that were subjected to solvolysis in 80% (v/v) aqueous ethanol (80E) and in 97% (wt/wt) aqueous 2,2,2-trifluoroethanol (97T). Reactions were monitored by titration of the liberated acid with an automatic pH-stat. Activation parameters were calculated from rate constants determined at three temperatures. The extrapolated or measured rate constants and the activation parameters are presented in Table 1. The Hammett ρ^+ values for the chlorides **1** were calculated using simple regression analysis and are presented in Table 2 together with some other important data.



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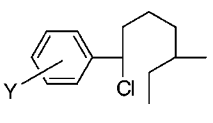
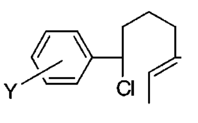


6S



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The activation parameters obtained in both solvents, for solvolysis of all chlorides **1**, are essentially the same as for the protio derivative (Y = H). Thus, all the values are consistent with rate-determining bicyclization, in which the high degree of order that is required in the transition state (large negative $\Delta S^{\ddagger}$) is overcompensated by a rather small $\Delta H^{\ddagger}$.[13] As we presumed, all substrates solvolyze by way of extended π-participation, making the system a reliable model for concerted bicyclization.

Table 2. Linear Free Energy Correlation of Some Benzylic Chlorides at 25 °C

compd	solvent	n[a]	ρ^{+} [b]	r[c]
6S[d]	97T	5	−6.28 ±0.25	0.997
6[d]	97T	4	−3.93 ± 0.10	0.998
		2	−6.21	
1	80E	5	−1.45 ± 0.03	0.999
	97T	5	−1.76 ± 0.04	0.999
3	95E	5	−1.86 ± 0.08	0.997
	80E	5	−1.81 ± 0.05	0.999
	97T	5	−1.56 ± 0.04	0.999

[a] Number of data points with (n = 5) or without (n = 4) the rate of the *p*-anisyl derivative. For n = 2 ρ^+ was obtained from *p*-anisyl and *p*-toluyl derivatives. [b] Uncertainties are standard errors of estimate. [c] Coefficient of correlation. [d] Compounds **6** and **6S**, see ref 16.

π-Participation of neighboring double bond(s) leads to charge delocalization away from the reaction center. Thus, the magnitude of the Hammett ρ^+ value, which can be used as a measure of the charge "seen" by the aromatic ring at the reaction center,[14] the electronic demand,[11a] or the charge delocalization,[15] should be very indicative of assistance by neighboring double bonds. The ρ^+ value for **6** is considerably higher than that for **6S** (−3.93 vs −6.28, Table 2) as expected.[16] This is caused by participation of the neighboring double bond. In the case of the *p*-anisyl group, the double-bond assistance is much attenuated by the strongly electron-donating *p*-methoxy substituent. A breakdown of the linear Hammett relation in the case of the *p*-anisyl compound (Figure 1) suggests that the assisted process is the major reaction pathway for all the variants except the *p*-anisyl substrate. That result is not suprising, since the ability of the *p*-anisyl group to attenuate double-bond participation has been previously shown.[17]

The ρ^+ values in both solvents for substrates **1** and **3** are much less negative than those of chlorides **6** (Table 2). Also, a better fit is obtained if the *p*-methoxy variant of **1** was included in the correlations (Table 2), while derivatives of structure **6** give a better correlation without the *p*-methoxy point. The neighboring group participation for substrates **1** is not overcome by the *p*-methoxy group, supporting a different, extended π-participation mechanism.

The values of ρ^+ obtained in both solvents (different nucleophilicity) are essentially the same, excluding the

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(11) For reviews, see: (a) Isaacs, N. *Physical Organic Chemistry*, 2nd ed.; Longman: London, Singapore, 1995; pp 146−192, 451−455, 650−654. See also: (b) Ruasse, M.-F.; Argile, A.; Dubois, J.-E. *J. Am. Chem. Soc.* **1984**, *106*, 4846−4849. (c) Hammett, L. P. *Physical Organic Chemistry*; McGraw-Hill: New York, 1970. (d) Brown, H. C.; Okamoto, Y. *J. Am. Chem. Soc.* **1958**, *80*, 4979−4987.

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(13) To the best of our knowledge there is no other solvolytic reaction with such a low $\Delta H^{\ddagger}$ as that for **1**, whose rate can be followed at conventional temperatures by conventional methods.

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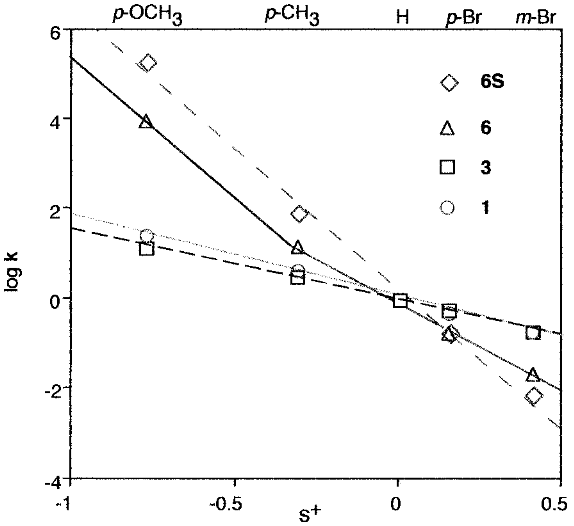
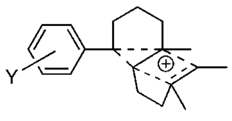


Figure 1. Hammett plots for some benzylic chlorides in 97% (wt/wt) aqueous 2,2,2-trifluoroethanol at 25 °C.

possibility that this extremely significant result is due to rate determining displacement by the solvent.[18] All the results can be attributed to the relatively small partially positive charge on the benzylic carbon of the transition state, since the charge is delocalized on at least five carbon atoms in concerted bicyclization, as is shown in structure **7**. Larger charge delocalization from the benzylic carbon in the transition state of **1** is consistent with the drastically less negative value of ρ^+ with an additional double bond (from -3.9 to -1.8 in 97T).



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Concerted Bicyclization of Squalene Derivatives. Unlike the results for the model structures **1** and **2**, which are all consistent with a concerted bicyclization, measurements with the squalene derivative are ambiguous in some aspects. For both systems **3** and **4** the activation parameters are in the range assigned to concerted monocyclization.[19-21] However, other parameters strongly support the extended π-participation mechanism. Ethanolysis of chloride **4** and its protio analogue gave a secondary β-deuterium KIE near unity ($k_H/k_D = 1.02 \pm 0.01$).[21] The identical result was obtained for **2**, leading to the conclusion that the squalene derivative also undergoes concerted bicyclization. The Hammett ρ^+ values obtained in three solvents with chlorides of the benzylic squalene derivatives **3** were much less negative than ρ^+ for the chlorides **6** (Table 2).[20] These values clearly suggest the extended π-participation mechanism, but it was not possible to decide whether bicyclization or even tricyclization is operative. It is evident from the data presented in Table 2 and shown in Figure 1 that the values of ρ^+ for systems **1** and **3** are essentially the same, leading to the conclusion that the squalene derivatives solvolyze by concerted bicyclization in the rate-determining step. Drastic reductions in the slope of the Hammett plots (Figure 1) for each additional double bond suggest a change in mechanism. Thus, solvolysis of chlorides **6S** proceeds through classical carbocationic intermediates. With chlorides **6** concerted monocyclization occurs, while with substrates **1** and **3** concerted bicyclization takes place. On the other hand, the superimposable Hammet plots for **1** and **3** demonstrate that they use the same reaction mechanism. The inconsistent values of the activation parameters could be rationalized using van Tamelen's[22] argument that squalene and some other polyenes assume a coiled conformation in polar solvents. Since all the solvents in which the solvolysis were carried out have high polarity, it is likely that the squalene-related substrates assume one of the many coiled conformations in which, by contrast to **1**, a necessary degree of order for participation is already achieved in the ground state. Concerted bicyclization is therefore favored since there is no requirement for the loss of many degrees of freedom in the transition state. It is important to mention that the latest theoretical calculations presented by Jorgensen et al. lead to the same conclusion, suggesting barrierless concerted formation of A and B rings from preorganized state of 2,3-epoxysqualene.[23] Tricyclization is probably not possible because a very defined structure in the transition state is needed that cannot be achieved due to the unfavorable entropy of activation.

Experimental Section

General Methods. All reactions requiring anhydrous conditions were carried out under inert atmosphere (argon). Dichloromethane (CH_2Cl_2) was dried over molecular sieves 4A. Tetrahydrofuran (THF) and diethyl ether (ether) were distilled and dried over sodium. The petroleum ether used had a boiling range of 40−60 °C. Whenever required, the reactions were conducted in oven-dried glassware under dry argon. For column chromatography, Merck silica gel (mesh 70−230) was used. TLC was performed on silica gel-coated plastic sheets (Merck TLC-plastic sheets silica gel 60) with vapors of I_2 as detector. ^1H and ^{13}C NMR spectra were recorded on a 300 MHz spectrometer using $CDCl_3$ as solvent. Chemical shifts are reported in ppm (δ) relative to Me_4Si as an internal standard. IR spectra (cm^{-1}) were measured on neat compounds.

1-Bromo-4,8-dimethyl-4,8-decadiene. Procedures described by le Noble et al.,[10] which include Johnson's[12] introduction of two trans trisubstituted double bonds, were used. A reaction scheme with almost the same procedure was published earlier by our group.[8] A novel procedure for preparation and purification of bromide **5** was employed that was described in our previous paper,[20] with 95.1% yield. ^1H NMR ($CDCl_3$) δ 1.56−1.59 (m, 9H, $C{=}CCH_3$), 1.91−2.13 (m, 8H, CCH_2C), 3.35 (t, 2H, $J = 6.74$ Hz, CH_2Br), 5.13−5.21 (m, 2H, $C{=}CH$); ^{13}C NMR ($CDCl_3$) δ 13.10, 15.33, 15.53, 26.28, 30.63, 33.06, 37.60, 39.38, 118.44, 125.74, 132.80, 135.40.

1-Phenyl-5,9-dimethyl-5,9-undecadienol. A suspension of lithium (Li) powder (300 mg, 43.22 mmol), granulated Li (300 mg, 43.22 mmol), dry THF (5 mL) and very little (10 μL) CH_3I was refluxed under a slow stream of argon for 10−15 min. The flask was placed in the ultrasonic bath (100 W, 30 kHz), and then a solution of bromide **5** (1.2 g, 4.89 mmol) and

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[18] (a) Harris, J. M.; Schadt, F. L.; Schleyer, P. von R.; Lancelot, C. J. J. *Am. Chem. Soc.* **1969**, *91*, 7508−7510 and ref 1a cited therein.

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benzaldehyde (0.432 g, 4.07 mmol) in 50 mL of dry THF was added dropwise to the stirred mixture. The temperature was held around 0 °C. After all the solution was added, the reaction mixture was by turns stirred with the magnetic stirrer and the ultrasonic bath for additional hour. The progress of the reaction was checked by TLC. During that period of time the color of the Li surface changed from dull matt to a golden silvery sheen. The excess of Li was filtered off, the filtrate was treated with a saturated aqueous solution of NH_4Cl (three times), and the alcohol was extracted three times with ether. The ether layers were combined, washed with a saturated aqueous solution of $NaHCO_3$ (three times), and dried over anhyd Na_2SO_4. The ether was evaporated, and the product was purified on a silica column. Unreacted bromide was removed with petroleum ether, other impurities were removed with petroleum ether/CH_2Cl_2 mixture (4:1), and the pure alcohol was eluted with petroleum ether/CH_2Cl_2 mixture (1:1). Evaporation of the pooled alcohol-containing fractions yielded 205.85 mg (18.56%) of the pure product: IR (neat) 3410 cm^{-1} (b, OH); ^1H NMR ($CDCl_3$) δ 1.56−1.60 (m, 9H, $C{=}CCH_3$), 1.97−2.06 (m, 10H, CCH_2C), 4.66 (t, 1H, J = 6.46, Ph(OH)CH), 5.10 (t, 1H, J = 6.45, ${=}CHCH_2{-}$), 5.20 (q, 1H, J = 6.46, ${=}CHCH_3$), 7.30−7.35 (m, 5H, Ph); ^{13}C NMR ($CDCl_3$) δ 13.05, 15.36, 15.47, 23.71, 26.29, 38.24, 39.13, 39.46, 74.39, 118.21, 124.54, 125.80, 127.37, 128.32, 134.55, 135.63, 144.85.

1-(4-Methoxyphenyl)-5,9-dimethyl-5,9-undecadienol. The procedure is the same as described above. From 200 mg (29 mmol) of powdered Li, 200 mg (29 mmol) of granulated Li, 1.2 g (4.9 mmol) of bromide **5**, and 0.56 g (4.1 mmol) of anisaldehyde was obtained 220.9 mg (17.8%) of pure alcohol: IR (neat) 3430 cm^{-1} (b, OH), 3430 (O−H); ^1H NMR ($CDCl_3$) δ 1.54−1.59 (m, 9H, $C{=}CCH_3$), 1.94−2.04 (m, 10H, CCH_2C), 3.78 (s, 3H, p-CH_3O), 4.57 (t, 1H, J = 6.6, Ar(OH)CH), 5.08 (t, 1H, J = 6.45, ${=}CHCH_2{-}$), 5.18 (q, 1H, J = 6.46, ${=}CHCH_3$), 6.85 (d, 2H, J = 8.7, m-CH_{Ar}), 7.23 (d, 2H, J = 8.7, o-CH_{Ar}); ^{13}C NMR ($CDCl_3$) δ 13.02, 15.33, 15.44, 23.75, 26.26, 38.12, 39.12, 39.42, 54.96, 73.90, 113.58, 127.03, 134.57, 136.98, 118.16, 124.43, 135.60, 158.83.

1-(4-Methylphenyl)-5,9-dimethyl-5,9-undecadienol. The procedure is the same as described above. From 270 mg (38.9 mmol) of powdered Li, 220 mg (31.7 mmol) of granulated Li, 1 g (4.08 mmol) of bromide **5**, and 0.41 g (3.41 mmol) of p-toluylaldehyde was obtained 258 mg (26,5%) of pure alcohol: IR (neat) 3390 cm^{-1} (b, O−H); ^1H NMR ($CDCl_3$) δ 1.54−1.58 (m, 9H, $C{=}CCH_3$), 1.94−2.07 (m, 10H, CCH_2C), 2.32 (s, 3H, p-$CH_3{-}$), 4.57 (t, 1H, J = 6.6, Ar(OH)CH), 5.08 (t, 1H, ${=}CHCH_2{-}$), 5.18 (q, 1H, ${=}CHCH_3$), 7.12 (d, 2H, J = 7.86, m-CH_{Ar}), 7.19 (d, 2H, J = 7.86, o-CH_{Ar}); ^{13}C NMR ($CDCl_3$) δ 13.02, 15.34, 15.47, 23.75, 26.29, 38.18, 39.15, 39.46, 20.80, 74.18, 118.17, 124.46, 134.58, 135.61, 136.94, 125.76, 128.97, 141.90.

1-(4-Bromophenyl)-5,9-dimethyl-5,9-undecadienol. The procedure is the same as described above. From 270 mg (38.9 mmol) of powdered Li, 260 mg (37.5 mmol) of granulated Li, 1.2 g (4.9 mmol) of bromide **5**, and 0.75 g (4.08 mmol) of 4-bromobenzaldehyde was obtained 130.4 mg (9.12%) of pure alcohol: IR (neat) 3490 cm^{-1} (b, OH); ^1H NMR ($CDCl_3$) δ 1.55−1.59 (m, 9H, $C{=}CCH_3$), 1.96−2.05 (m, 10H, CCH_2C), 4.63 (t, 1H, J = 6.46, Ar(OH)CH), 5.09 (t, 1H, J = 6.46, ${=}CHCH_2{-}$), 5.19 (q, 1H, ${=}CHCH_3$), 7.21 (d, 2H, J = 8.14, o-CH_{Ar}), 7.46 (d, 2H, J = 8.14, m-CH_{Ar}); ^{13}C NMR ($CDCl_3$) δ 13.05, 15.36, 15.47, 23.52, 26.28, 38.26, 39.06, 39.44, 73.70, 118.22, 124.68, 125.80, 128.34, 134.38, 127.54, 131.40, 143.81.

1-(3-Bromophenyl)-5,9-dimethyl-5,9-undecadienol. The procedure is the same as described above. From 150 mg (21.6 mmol) of powdered Li, 400 mg (57.6 mmol) of granulated Li, 1.89 g (7.7 mmol) of bromide **5**, and 1.18 g (6.4 mmol) of 3-bromobenzaldehyde was obtained 90.15 mg (4.0%) of pure alcohol: IR (neat) 3400 cm^{-1} (b, OH); ^1H NMR ($CDCl_3$) δ 1.55−1.60 (m, 9H, $C{=}CCH_3$), 1.99−2.06 (m, 10H, CCH_2C), 4.66 (t, 1H, Ar(OH)CH), 5.12−5.21 (m, 2H, ${=}CHCH_2{-}$ and ${=}CHCH_3$), 7.34−7.51 (m, 4H, CH_{Ar}); ^{13}C NMR ($CDCl_3$) δ 13.07, 15.34, 15.54, 25.94, 26.25, 30.40, 35.73, 39.39, 39.44, 65.08, 118.34, 124.76, 125.22, 126.91, 127.54, 128.48, 130.46, 134.54, 135.58, 140.86.

Chlorides 1. 1-Chloro-1-phenyl-5,9-dimethyl-5,9-undecadiene (**1**-H), (1-chloro-1-(4-methoxyphenyl)-5,9-dimethyl-5,9-undecadiene (**1**-p-OCH_3), 1-chloro-1-(4-methylphenyl)-5,9-dimethyl-5,9-undecadiene (**1**-p-CH_3), 1-chloro-1-(4-bromophenyl)-5,9-dimethyl-5,9-undecadiene (**1**-p-Br), and 1-chloro-1-(3-bromophenyl)-5,9-di-methyl-5,9-undecadiene (**1**-m-Br), respectively, were prepared from the corresponding alcohols and thionyl chloride ($SOCl_2$). The appropriate alcohol was dissolved in 10−15 mL of petroleum ether (bp 40−60 °C), the solution was cooled to −15 °C, and $SOCl_2$ was added dropwise. The reaction mixture was stirred for 2 h under reduced pressure (about 520−560 mmHg, 693−747 mbar) to remove the liberated HCl and SO_2 continuously. Then, the petroleum ether was evaporated and crude chloride was used for kinetic measurements. Further purification proved to be unnecessary since the solvolysis rates were found to be independent of contamination.

Kinetic Measurements. Solvolysis rates were followed in 80% (v/v) aqueous ethanol (80E) and 97% (wt/wt) aqueous 2,2,2-trifluoroethanol (97T) titrimetrically by means of a pH-stat (end-point titration, pH = 6.85). Typically, 0.02 mmol of the chloride **1** was dissolved in 20 mL of the solvent at the required temperature thermostated ±0.05 °C, and the liberated HCl was continuously titrated by using a 0.008 M solution of NaOH in the same solvent mixture. Individual measurements could be described by the first-order low from 15% up to at least 80% completion. First-order rate constants were calculated from about 100 determinations by using a nonlinear least-squares program. Measurements were usually repeated three to seven times. Activation parameters were calculated from rate constants at three different temperatures.

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Supporting Information Available: Spectral data and C, H, N analysis for bromide **5** and all parent alcohols of **1** (19 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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