Transannular Hydride Shifts. A Mechanistic Study in the Longifolene Series[1a,b]

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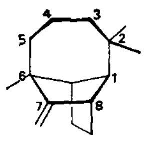
Abstract: A 1:5 hydride shift occurs simultaneously with neopentylic rearrangement during the ethanolysis of medium-size ring bromides (**4a–4i**) in the longifolene series. Product analyses and the results of a kinetic study show the occurrence of two competitive mechanisms with distinct rate-determining steps. When transannular hydride migration predominates, the reaction is accelerated. This is interpreted in terms of σ(C–H) assistance in the rate-determining step of the transannular reaction.

Neighboring-group participation in the solvolysis of alkyl halides or sulfonates is an accepted fact when it involves nonbonding electrons on the participating group.[3] Participation of π electrons appears also to be an accepted phenomenon,[4] whereas in recent years much controversy has centered around the interesting problem of σ(C–C) participation.[5] The possibility of participation of σ(C–H) electrons to solvolytic displacement has been well discussed in simple acyclic systems,[6] in cyclohexyl,[7] or in bicyclo[2.2.1]heptyl derivatives,[8,9] but is much less documented in medium rings[10] (transannular reactions).

We now present results proving that, at least in the series we have studied, solvolysis accompanied by *1:5-hydride transfer* can be appreciably accelerated by comparison with solvolysis accompanied by carbon–carbon rearrangement. More specifically, in the cases described, transannular hydride shift is an accelerating factor compared with neopentylic rearrangement. This will provide the basis for a discussion of σ(C–H) participation. The substrate used is *longifolene* **1**. The compact skeleton of this tricyclic sesquiterpene is particularly prone to far-reaching rearrangements, some of which have already been the subject of mechanistic studies of rather general consequences.[1,11] This paper describes a mechanistic study of the solvolysis of a series of 3α-bromo derivatives of longifolene. The perspective drawings **1′** and **4′** of the longifolene molecule **1** and of the derivatives **4**, in which we have emphasized the presence of a bridged cyclooctane ring, show two transannular carbon atoms, C-3 and C-7, in a very close proximity. The particular conformation depicted in formula **1′**, which ensures this proximity, was originally shown to be the more stable one, and to be practically blocked, by a conformational analysis of the "large bridge" C(1)–C(6).[11] This conformation has been proved directly by several X-ray analyses.[12]



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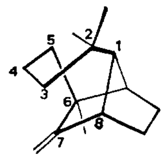

1′

The proximity of C-3 and C-7 is responsible for easy *transannular cyclizations* between these positions, to give the adamantoid system **3** by solvolysis of 3α-bromolongifolene **2**.[13] It is also responsible for *transannular hydrogen transfers* between C-3 and C-7: free-radical **3** → **7** hydrogen transfers (the first homolytic transannular H shifts observed)[11] and ionic **7** → **3** hydride transfers,[1,11] to which is devoted the present study (Figure 1).

The solvolytic behavior of some derivatives of 3α-bromolongifolane **4** has already been described from a preparative point of view.[11] Whereas 3α-bromo-(*7βH*)longifolane **4** ($Z = CH_3$) gave, as the sole product isolated, longifolene itself (by a C-7 → C-3 hydride shift), methyl 3α-bromo(*7βH*)longifolate **4** ($Z = CO_2CH_3$) underwent ring contraction (Figure 2). This had been interpreted by the competition of two reaction routes, one (route b) being favored only when a developing positive charge is stabilized at C-7 by an electron-donating substituent Z.

A direct kinetic comparison of these two routes is impossible due to the different electronic character of the Z substituents. The Taft–Hammett treatment on a series of compounds has to be used.[14,15]

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(1) (a) Longifolene. XVI. Part XV: J. Lhomme and G. Ourisson, *Tetrahedron*, **24**, 3177 (1968). (b) This work was supported in part by grants from F. Hoffmann-La Roche, Basle, and Roure-Bertrand et Justin Dupont, Grasse.

(2) Laboratory associated with the National Center of Scientific Research.

(3) B. Capon, *Quart. Rev., Chem. Soc.*, **18**, 45 (1964); L. A. Paquette and R. W. Begland, *J. Amer. Chem. Soc.*, **90**, 5159 (1968), and references therein; D. D. Robert and W. Hendrickson, *J. Org. Chem.*, **34**, 2415 (1969).

(4) M. Hanack and H. J. Schneider, *Angew. Chem., Int. Ed. Engl.*, **6**, 666 (1967), and references therein.

(5) G. D. Sargent, *Quart. Rev., Chem. Soc.*, 20, 301 (1966).

(6) D. J. Cram and J. Tadanier, *J. Amer. Chem. Soc.*, **81**, 2737 (1959); S. Winstein and J. Takahashi, *Tetrahedron*, 2, 316 (1958).

(7) S. Winstein, B. K. Morse, E. Grunwald, H. W. Jones, J. Corse, D. Trifan, and H. Marshall, *J. Amer. Chem. Soc.*, 74, 1127 (1952); S. Winstein and N. J. Holness, *ibid.*, 77, 5562 (1955); M. Tichý, J. Hapala, and J. Sicher, *Tetrahedron Lett.*, 3739 (1969); R. Baker, J. Hudec, and K. L. Rabone, *Chem. Commun.*, 197 (1969).

(8) S. Winstein and D. Trifan, *J. Amer. Chem. Soc.*, 74, 1154 (1952); S. Winstein, E. Clippinger, R. Howe, and E. Vogelfanger, *ibid.*, **87**, 376 (1965).

(9) J. M. Jerkunića, S. Borčić, and D. E. Sunko, *Chem. Commun.*, 1488 (1968).

(10) A. C. Cope, M. M. Martin, and M. A. McKervey, *Quart. Rev., Chem. Soc.*, 20, 119 (1966); V. Prelog, E. Troxler, and H. H. Westen, *Helv. Chim. Acta*, **51**, 1679 (1968).

(11) D. Helmlinger and G. Ourisson, *Justus Liebigs Ann. Chem.*, **686**, 19 (1965).

(12) J. Cl. Thierry and R. Weiss, *Tetrahedron Lett.*, 2663 (1969).

(13) D. Helmlinger and G. Ourisson, *Tetrahedron*, **25**, 4895 (1969).

(14) This method, introduced by Streitwieser[15a] in his work on solvolysis, has recently been used to distinguish between assisted and nonassisted solvolysis pathways.[15b,15c]

(15) (a) A. Streitwieser, Jr., *J. Amer. Chem. Soc.*, **78**, 4935 (1956); "Solvolytic Displacement Reactions," McGraw-Hill, New York, N. Y., 1962, pp 122, 146; (b) Ch. J. Lancelot, J. J. Harper, and P. von R. Schleyer, *J. Amer. Chem. Soc.*, **91**, 4294 (1969); (c) P. G. Gassman,

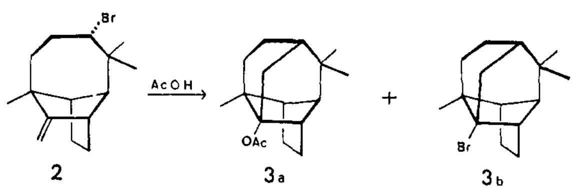


Figure 1. Solvolysis of 3α-bromolongifolene.

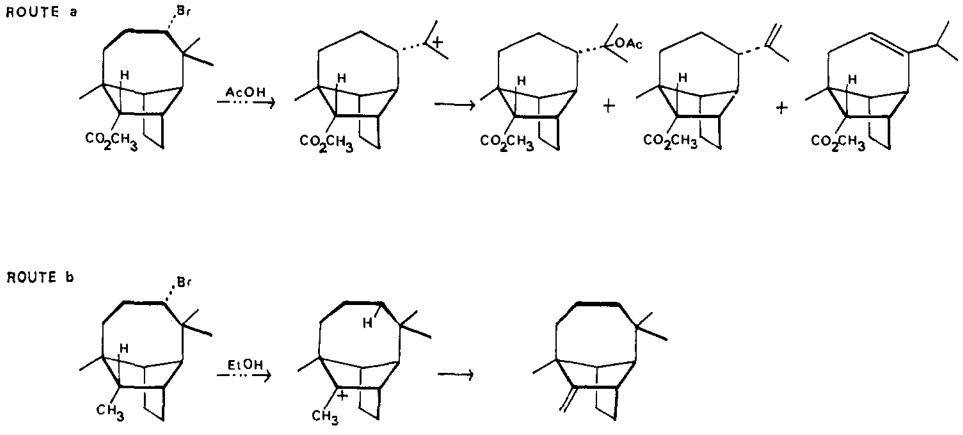


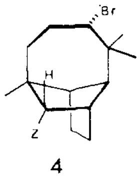
Figure 2. Solvolysis of 3α-bromo derivatives of longifolane and methylisolongifolate.

One could expect either one of two types of mechanistic situations: *either* the rate-determining step, the ionization, is followed by two competitive reactions, in which case the effect of Z on the rate of reaction must follow a linear Taft–Hammett relationship; *or* there are, for a series of compounds, two competitive reactions, each one being rate determining for its own path, and the result should be a breakdown of any Taft–Hammett linear correlation.

Our results are in favor of two competitive reactions. We shall describe them first, and then compare them with published results in the cyclooctane and in the bicyclo[3.3.1]nonane series.

Results

Nine substances of the general type **4**, **4a**–**4i**, chosen to cover a wide range of inductive effects of the substituents Z, were prepared by standard methods summarized in Chart I and described in the Experimental Section.



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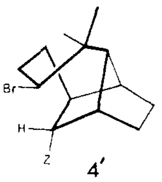
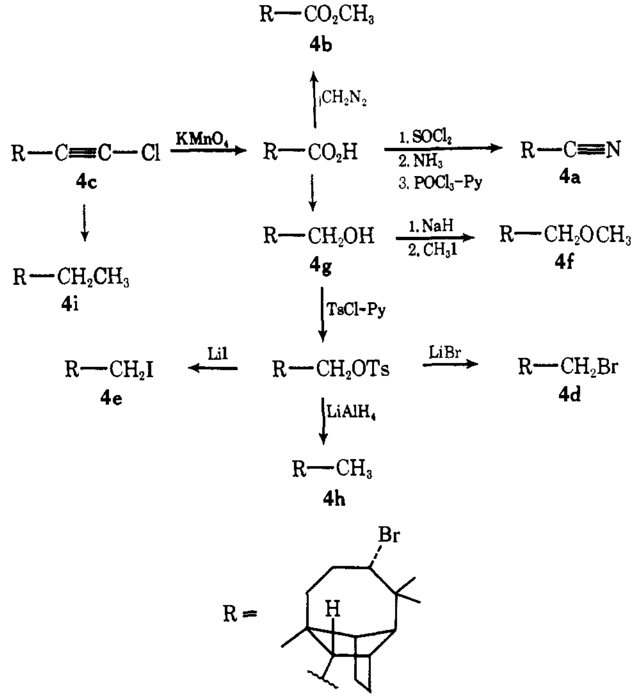


4′

The *rates of solvolysis* of these nine substances have been measured titrimetrically, in aqueous ethanol (EtOH, 80%, v/v) at 60°, up to 85–90% of completion (Table I). The slowest rate is obtained for the compound carrying the most electronegative group (**4a**, Z = CN), and the highest rates correspond to the substrates carrying the best electron-donor substituents (**4h**, Z = CH_3 and **4i**, Z = CH_2CH_3). The Taft–Hammett treatment[16] gives a smooth curve (Figure 3) rather than a straight line. For strongly electron-attracting groups (CN, CO_2CH_3), the reaction follows an approximate Taft–Hammett relationship with $\rho_1 \simeq -0.3$; for strongly electron-donating groups (C_2H_5, CH_3, CH_2OH), the reaction is faster and follows an approximate Taft–Hammett relationship with $\rho_2 \simeq -1.6$.[17] The entropy of activation remains approximately the same, small and negative, in the series. The relative acceleration of the reaction for electron-donating groups Z is essentially due to an effect on the

Chart I



J. L. Marshall, J. G. Macmillan, and J. M. Hornback, *J. Amer. Chem. Soc.*, **91**, 4282 (1969).

(16) (a) Taft constants have been found in the literature for most of the substituents Z, or have been derived from known values by usual procedures;[16b] (b) R. W. Taft, Jr., "Steric Effects in Organic Chemistry," M. S. Newman, Ed., Wiley, New York, N. Y., 1956, p 556.

(17) From the product analysis (*vide infra*), it was not possible to obtain definitive evidence for a reaction involving *one* mechanism *only* (hydride migration or ring contraction), but only for overwhelmingly predominant individual reactions. Even for the nitrile **4a**, a small amount of hydride shift may have occurred; similarly, even for the opposite cases **4h** and **4i**, we have no positive evidence against the occurrence of some ring contraction (<10%). Therefore, the ratio $\rho_2:\rho_1$, as evaluated here, may be a minimum value approximating the corresponding ratio for the "pure" individual reactions in competition.

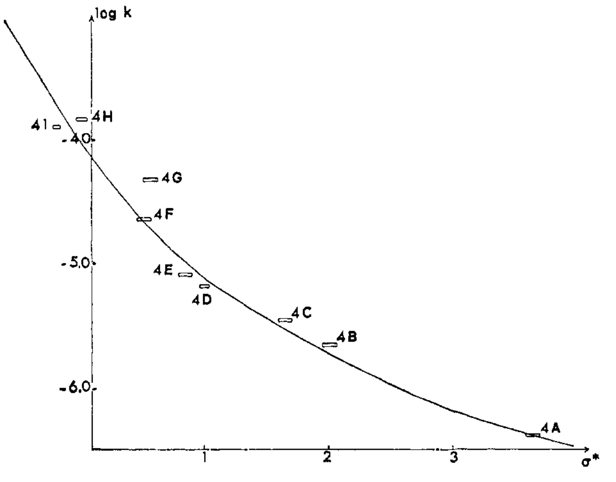


Figure 3. Taft–Hammett plot for the solvolysis of **4a**–**4**i.

activation enthalpy (Table II). Some of the products have been identified in previous studies as longifolene **1** (ethanolysis of **4h**), and ring-contracted products (acetolysis of **4b**, Figure 1, route a). Due to extreme difficulties in separating and identifying the solvolysis products, we have only analyzed those of the two slowest (**4a**, **4b**), and of the two fastest reactions (**4h**, **4i**). Table III summarizes our results, obtained by isolation of the major products and by a quantitative evaluation of the nmr spectrum of the crude reaction mixture. These results are not entirely satisfactory inasmuch as we have in no case been able to account for more than 90%, and in one case for only 60% of the reaction products. The clear fact remains however that with the nitrile **4a**, carrying the most electron-attracting group Z studied, *at least* 70% of the solvolysis is accompanied by ring contraction, whereas with the most electron-donating group Z studied, substance **4i** gives *at least* 90% transannular hydrogen transfer.

Table I

Z	σ*	k,[a] sec^{-1}, 60°	k_{rel}
CN (**4a**)	+3.64[e]	(6.80 ± 0.10)10^{-7}	1
CO_2CH_3 (**4b**)	+2.00	(2.29 ± 0.03)10^{-6}	3
C≡C–Cl (**4c**)	+1.66[e]	(3.64 ± 0.04)10^{-6}	5
CH_2Br[b] (**4d**)	+1.00	(6.78 ± 0.05)10^{-6}	10
CH_2I[c] (**4e**)	+0.85	(8.25 ± 0.20)10^{-6}	12
CH_2OCH_3 (**4f**)	+0.52	(2.29 ± 0.07)10^{-6}	33
CH_2OH[d] (**4g**)	+0.555	(4.80 ± 0.04)10^{-5}	70
CH_3 (**4h**)	0	(1.49 ± 0.03)10^{-4}	220
CH_2–CH_3 (**4i**)	−0.10	(1.28 ± 0.02)10^{-4}	190

[a] *k* is the average of the individual first-order constants calculated from each independent titrimetrical measurement; the uncertainty indicated is the median experimental deviation. [b] After more than 60% solvolysis of the secondary bromide (C-3), titrimetric measurements are disturbed by slow solvolysis of the primary bromide (C-15). [c] As the primary iodide solvolyzes nearly as fast as the secondary bromide, the *k* value was in this case graphically obtained by extrapolation of the function log [**4e**] = *f*(*t*). [d] Solvolysis of **4g** (Z = CH_2OH) gives isolongifolic aldehyde, which probably disproportionates to give Cannizaro products. Even when the solvolysis is run under an argon atmosphere, to avoid autoxidation of the aldehyde to the acid, the "infinite" experimental measurement shows some 6% more acidity than the expected value. *k* was in this case calculated from three independent runs, stopped after 50% reaction. [e] Values calculated by procedures indicated in ref 16b; the other values are taken from that reference.

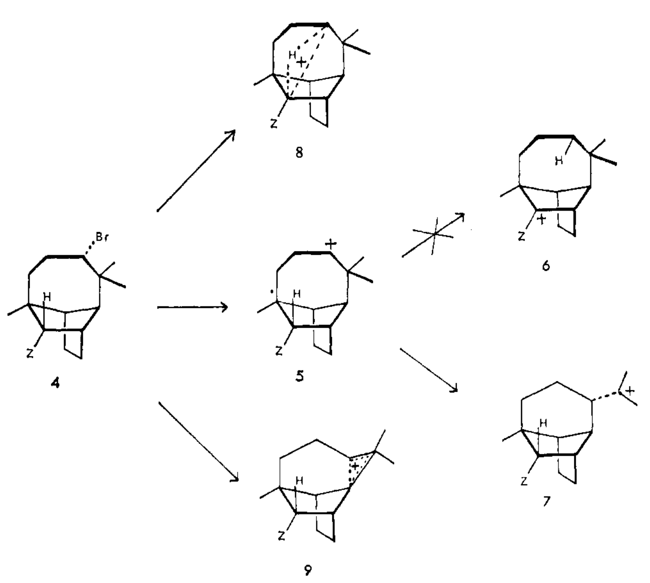


Figure 4. Potential ionic intermediates mentioned in the mechanistic discussion.

Interpretation and Discussion

A difference in mechanism suggested by the product analysis going from the nitriles (ring-contraction products) to longifolene (hydride-shift product), is confirmed by the nonlinear Taft–Hammett plot. Our results *exclude* the simplest mechanistic hypothesis, that of a rate-determining ionization to the classical carbonium ion **5**, followed by fast, competitive reactions of this carbonium ion: ring contraction to the ion **7** or hydrogen transfer to the ion **6** (Figure 4). Our results *imply* on the contrary a direct role of H-7 in the rate-determining step and it seems reasonable to assume that the H transfer occurs through a faster mechanism than the ring contraction. This appears to be compatible with *three* alternative descriptions.

In the first description, based on the "nonclassical ion" terminology,[18,19] the ionization of the C–Br bond would be σ(C–H) assisted to the ion **8**, the ring contraction being either concerted to the nonclassical ion **9** or stepwise (ion **5** giving ion **7**). In this description, one would most probably admit the hypothesis of an assisted neopentylic ring contraction;[20] one would then consider that the anchimeric assistance by the C–H bond accelerates the ionization *more* than does the assistance by the C–C bond. The 200-fold rate factor we observe between the two extreme cases (**4a** and **4i**) would then be a minimum value for the assistance due to the C–H bond.[22]

In any case, the results show the involvement of H-7 in the rate-determining step. There are at least four main factors which would favor the facile migration of

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[18] P. D. Bartlett, "Non-classical Ions," W. A. Benjamin, New York, N. Y., 1965.

[19] The use of this terminology does not imply unanimous adherence of the three authors to the dogma of nonclassical ions. This will be clear in the sequel.

[20] W. G. Dauben and J. L. Chitwood, *J. Amer. Chem. Soc.*, **90**, 6876 (1968); 92, 1624 (1970). As we shall mention later, in this hypothesis, the isolation of longifolene from 4h would in itself indicate participation of the C–H bond in the rate-determining step.[21]

[21] S. Winstein and R. L. Hansen, *ibid.*, **82**, 6206 (1960).

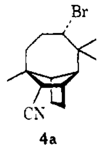
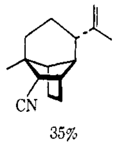
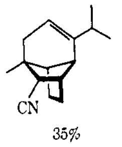
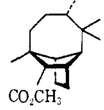
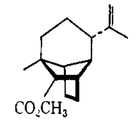
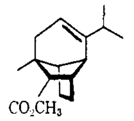
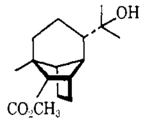
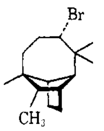
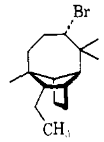
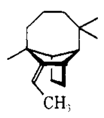
[22] In fact, the 200-fold rate factor observed includes also the inductive, long-range acceleration due to Z. This must certainly be of minor significance here. Our data cannot however be used to derive individual rate factors.

Table II

Z	T, °C	k, $\sec^{-1}$, $\times 10^{-5}$	$\Delta H^{\ddagger}$, kcal mol^{-1} [a]	$\Delta S^{\ddagger}$, cal deg^{-1} mol^{-1}
CH_2CH_3 (**4i**)	40.0 ± 0.1	1.15 ± 0.05	24.45 ± 0.65	−3.3 ± 2.1
CH_3 (**4h**)	40.0 ± 0.1	1.31 ± 0.03	24.75 ± 0.45	−2.2 ± 1.4
$C{\equiv}C\text{-}Cl$ (**4c**)	80.0 ± 0.1	3.53 ± 0.02	25.95 ± 0.25	−6.1 ± 0.8
CO_2CH_3 (**4b**)	80.0 ± 0.1	2.48 ± 0.06	27.20 ± 0.40	−2.7 ± 1.5

[a] For k values at 60°, see Table I.

Table III

Starting material	Solvolysis products		
 **4a**	 35%	 35%	
 **4b**	 30%	 20%	 ≥10%
 **4h**	 80%		
 **4i**	 90%		

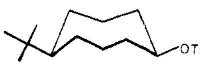
this hydrogen as a hydride ion: (a) H-7 is approximately equidistant from C-7 and C-3, and the C–H bond is parallel to the developing p orbital at the cationic center C-3; (b) the migrating hydride constitutes a leaving group from the exo position of a *tert*-bicyclo[2.2.1]heptyl system; (c) the migration leads from a secondary carbonium ion to a tertiary one; (d) an increase of the sp^2 character of C-7 removes the eclipsing strain of the two groups substituting C-6 and C-7 in the starting structure.

The involvement of H-7 in the rate-determining step and the four favorable factors listed above are of course independent of the theoretical interpretation used. They can be transferred directly into the interpretation favored by one of the authors (G. O.), that of competitive internal S_N2-like reactions involving either the C–H or the C–C bonds.[23] A third interpretation, based on a *predissociation* into a tight ion pair,[24] involves the same assistance of the migrating hydrogen atom, and is in fact indistinguishable from the preceding interpretation. The bromo derivative **4** would, in a reversible reaction, give a tight ion pair. This would lead to no observable reaction, and would be followed by two competitive internal displacements, either by the C(1)–C(2) bond, or by the C(7)–H bond, to give the ions 6 and 7.[25] In this case and in the preceding one, the molecular species with H-7 partly linked to C-3 would be a transition state, not an intermediate as in the nonclassical ion picture, but the kinetic situation would be the same.

Experiments had already been devised to try to decide between free carbonium ions and nonclassical ions as putative intermediates in two series somewhat analogous to longifolene.

In the *cyclooctyl series*, transannular hydride migrations are of course well known.[26–28] Their intimate mechanism appears however to be controversial.[29–31] A participation of the σ(C–H) bond to solvolysis was considered to be demonstrated by the acceleration found in the acetolysis of *cis*-5-*tert*-butylcyclooctyl tosylate **10**, by a factor of 53 compared with the trans epimer **11**, for which such a participation is sterically impossible.[32]

In another study, the opposite conclusion was reached from a study of the kinetic isotope effects of 3,3,4,4,5,5,6,6-octadeuteriocyclooctyl tosylate; the observed effects are considered to be too small to support σ(C–H) participation.[33]



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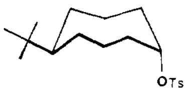

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A similar ambiguity exists in the *bicyclo*[*3.3.1*]-*nonane series*. There again, the existence of transannular shifts is quite clear,[34] but not their intimate mechanism. Acetolysis of the tosylate **12** gives less than 5% rearranged product **13** formed by 7 → 3 hydride transfer.[35] Electron-donating substituents at C-7 favor the hydride transfer: the homolog **14** of **12** gives a little more rearranged product **15** than the "normal" solvolysis product **16**.[36]

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(23) *Cf.* for another example: P. Ourisson and G. Ourisson, *Bull. Soc. Chim. Fr.*, 1415 (1954).

(24) V. J. Shiner, Jr., and W. Dowd, *J. Amer. Chem. Soc.*, **91**, 6528 (1969); V. J. Shiner, Jr., R. D. Fischer, and W. Dowd, *ibid.*, **91**, 7748 (1969); R. A. Sneen and J. W. Larsen, *ibid.*, **91**, 362, 6031 (1969).

(25) The observed titrimetric rate constant measures the release of Br^- from the tight ion pair.

(26) A. C. Cope, S. W. Fenton, and C. F. Spencer, *J. Amer. Chem. Soc.*, **74**, 5884 (1952); A. C. Cope, A. H. Keough, P. E. Peterson, H. E. Simmons, Jr., and G. W. Wood, *ibid.*, **79**, 3900 (1957); A. C. Cope, A. Fournier, Jr., and H. E. Simmons, *ibid.*, **79**, 3905 (1957).

(27) A. C. Cope and D. M. Gale, *ibid.*, **85**, 3743 (1963).

(28) N. L. Allinger and S. Greenberg, *ibid.*, **84**, 2394 (1962).

(29) A. C. Cope and D. M. Gale, *ibid.*, **85**, 3747 (1963).

(30) See ref 10, p 123.

(31) V. Prelog and J. G. Traynham, "Molecular Rearrangements," Vol. 1, P. de Mayo, Ed., Wiley, New York, N. Y., 1963, p 612.

(32) N. L. Allinger and W. Szkrybalo, *Tetrahedron*, **24**, 4699 (1968).

(33) A. A. Roberts and C. B. Anderson, *Tetrahedron Lett.*, 3883 (1969).

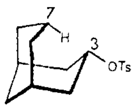
(34) R. A. Appleton and S. H. Graham, *Chem. Commun.*, 297 (1965); H. Dugas, R. A. Allison, Z. Valenta, K. Wiesner, and C. M. Wong, *Tetrahedron Lett.*, 1279 (1965); W. A. Ayer and K. Piers, *Chem. Commun.*, 541 (1965); R. A. Appleton, J. R. Dixon, J. M. Evans, and S. H. Graham, *Tetrahedron*, **23**, 805 (1967).

(35) M. A. Eakin, J. Martin, and W. Parker, *Chem. Commun.*, 298 (1968).

(36) M. A. Eakin, J. Martin, W. Parker, C. Egan, and S. H. Graham, *ibid.*, 337 (1968).

Table IV

Product	Mp, °C	[α]D, deg	Nmr, J in Hz (CCl_4)				
			CH_3-12	CH_3-13	CH_3-14	H-3	H-15
4a (Z = CN)	105–106	−15	61 (s)	63 (s)	59 (s)	262 (dd), $J = 4, J = 9$	
4d (Z = CH_2Br)	70–75		73 (s)	73 (s)	53 (s)	267 (dd), $J = 4, J = 9$	203 (d), $J = 7.5$
4f (Z = CH_2I)	111–112	−39	73 (s)	73 (s)	51 (s)	273 (dd), $J = 4, J = 9$	189 (d), $J = 8.5$
4g (Z = CH_2OCH_3)	Liquid	−61	71 (s)	72.5 (s)	50 (s)	279 (dd), $J = 4, J = 9$	196 (d), $J = 6$
4l (Z = CH_2CH_3)	41.5–42.5	−83	69 (s)	72 (s)	46 (s)	277 (dd), $J = 4, J = 10$	



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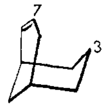

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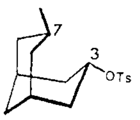

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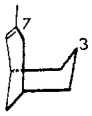

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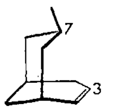

16

This observation is quite similar to the formation of longifolene from 3α-bromolongifolane **4h**, and the analogy should be expected, as the two systems are very similar geometrically; the distance C(3)–C(7) is 3.06 Å in the bicyclo[3.3.1]nonane series[37] and 3.17 Å in the longifolene series.[12] However, in the bicyclic series, no kinetic isotope effect has been observed on the rate of solvolysis of the 7-deuterio analog of **14**, a fact which has been considered to exclude σ(C–H) participation.[36,38]

We do not believe this absence of a deuterium isotope effect shows the absence of σ(C–H) assistance. Migration of H-7 results in the production of a tertiary positive center. We know that for solvolysis, the transition state is very close to the first intermediate.[39] Westheimer's treatment[40] shows that "low isotope effects will occur when the critical configuration" (the transition state) "resembles either that in the reactants or the products, and that for intermediate cases the full theoretical maximum will be shown"[41]

C-7················H···C-3, low isotope effect

C-7··········H··········C-3, large isotope effect

Therefore, σ(C–H) assistance to solvolysis in the bicyclo[3.3.1]nonane series should probably not involve a deuterium isotope effect in a dissymmetric case such as **14**. In the longifolene series, it is probable that this effect will also be very small, and, even if such an isotope effect were not observable, this would apparently be quite compatible with our demonstration of σ(C–H) assistance.

It is quite obvious that any conclusion at this point would be simpler if we could describe measurements of kinetic isotope effects in the longifolene series and of substituent kinetic effects in the bicyclononane series; we shall endeavour to make these results available.

It appears appropriate to mention also a related case, that of the brosylate **17**.[21] In this substance, one can dissect a nine-membered ring, blocked by three bridges so that there is no conformational mobility (see Figure 5). In this case, it has been unambiguously shown that H-5 participates in the rate-determining step: **17** undergoes solvolysis at a higher rate than **20**. No ring contraction product **19** is observed, whereas **21** is formed from **20**; when H-5 is replaced by D, a kinetic isotope effect is observed. (Note that in this case the migration is from a secondary to a secondary center, which might explain this isotope effect as the transition state must be more symmetrical here.) Winstein and Hansen[21] conclude that "neither the large rate factor nor even the isotope factor are as convincing as the absence of product like **21**, (to show) that hydrogen participation is occurring in the ionization step of (the solvolysis of) **17**." This conclusion, extended to the longifolene series, would imply that, if it were possible to be sure of σ(C–C) assistance to ionization when ring contraction occurs, then the observation of products of hydrogen

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(37) W. A. C. Brown, J. Martin, and G. A. Sim, *J. Chem. Soc.*, 1844 (1965); M. Dobler and J. D. Dunitz, *Helv. Chim. Acta*, **47**, 695 (1964).

(38) J. P. Schaefer and C. A. Flegal, *J. Amer. Chem. Soc.*, **89**, 5729 (1967); these authors, without excluding the possibility of σ(C–H) participation, nevertheless consider it to be improbable.

(39) G. S. Hammond, *J. Amer. Chem. Soc.*, 77, 334 (1955).

(40) F. H. Westheimer, *Chem. Rev.*, **61**, 265 (1961).

(41) D. V. Banthorpe, "Reaction Mechanisms in Organic Chemistry," Vol. 2, Elsevier, Amsterdam, 1963.

Mass spectra: Calcd, M+ =	Mass spectra: Found	Anal., %: Calcd	Anal., %: Found
		$C_{15}H_{22}BrN$	
295, 297 ($C_{15}H_{22}BrN$)	M^+ = 295, 297 $(M - CH_3)^+$ = 280, 282 $(M - Br)^+$ = 216	C, 61.02; H, 7.17;; N, 4.75; Br, 27.07	C, 61.05; H, 7.33; N, 4.80; Br, 26.71
362, 364, 366 ($C_{15}H_{24}Br_2$)	M^+ = 362, 364, 366 $(M - CH_3)^+$ = 347, 349, 351 $(M - Br)^+$ = 283, 285 $(M - Br - HBr)^+$ = 203		
		$C_{15}H_{24}BrI$	
410, 412 ($C_{15}H_{24}BrI$)	M^+ = 410, 412 $(M - CH_3)^+$ = 395, 397 $(M - Br)^+$ = 331 $(M - I)^+$ = 283, 285 $(M - I - HBr)^+$ = 203	C, 43.82; H, 5.82; Br, 19.43; I, 30.87	C, 44.14; H, 5.80; Br, 19.39; I, 30.38
		$C_{16}H_{27}BrO$	
314, 316 ($C_{16}H_{27}BrO$)	M^+ = 314, 316 $(M - CH_3OH)^+$ = 282, 284 $(M - Br)^+$ = 235 $(M - Br - CH_3OH)^+$ = 203	C, 60.95; H, 8.63	C, 61.39; H, 8.76
		$C_{16}H_{27}Br$	
298, 300 ($C_{16}H_{27}Br$)	M^+ = 298, 300 $(M - i\text{-}Pr)^+$ = 255, 257 $(M - HBr)^+$ = 218 $(M - Br)^+$ = 219 $(M - Br - CH_3)^+$ = 203	C, 64.21; H, 9.09; Br, 26.70	C, 64.53; H, 9.18; Br, 26.77

migration would be sufficient proof of H participation, even without our kinetic evidence.[20]

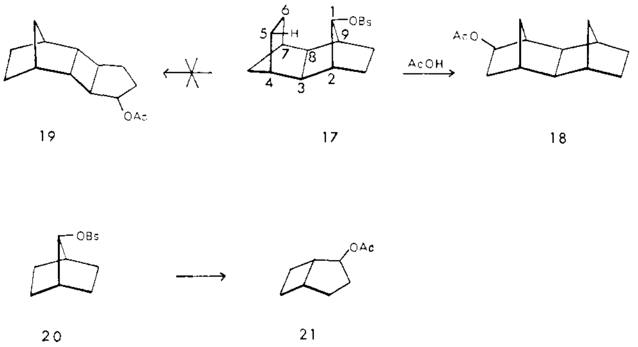


Figure 5. Solvolysis of a blocked cyclononyl derivative.

Conclusions

The conformational mobility of medium-size rings makes it difficult to interpret the intimate mechanisms of their reactions, where the exact conformation plays a dominant role. This is certainly true for the problem of σ(C–H) participation in hydride migrations in these systems, especially in the monocyclic series; it may even be true to some extent in the bicyclo[3.3.1]nonane series, in which a chair–boat conversion remains possible before solvolysis.

The cyclooctane ring which forms part of the structure of longifolene derivatives is very much hindered, and efficiently blocked by the two supplementary bridges, as well as by the *gem*-dimethyl group, which provides a "conformational anchor." The observed unambiguous intervention of the C–H bond in the rate-determining step of a 1,5 H shift in this case is probably due to the removal of any geometric ambiguity, as well as to the choice of a favorable method of investigation; we plan to use the same method in other similar series.

Experimental Section

The following instruments were used: melting points (mp), Reichert heating stage and microscope; infrared spectra (ir), Beckman IR-8A spectrophotometer; nuclear magnetic resonance spectra (nmr), Varian A-60, tetramethylsilane as internal reference; mass spectra, Thomson-Houston THN-208 double focusing spectrometer, direct inlet, 70 eV; specific rotations ([α]D), Perkin-Elmer 141 automatic polarimeter, chloroform solutions; gas chromatography, Aerograph Hy-Fi 600. Microanalyses were run by the Strasbourg Division of the Microanalysis Central Service of CNRS. Longifolene **1** was obtained by courtesy of Roure-Bertrand and Justin-Dupont, Grasse, France. Table IV summarizes physical data of all substances described in this paper for the first time.

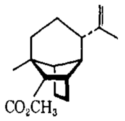
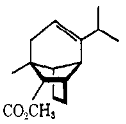
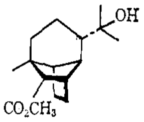
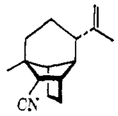
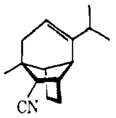
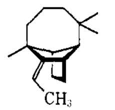
3α-Bromo-15-trichloromethyl(7β*H*)longifolane (4) (Z = CH_2CCl_3). The preparation of this substance as described previously[11] is too concise to be repeated easily. We therefore give a more detailed procedure. A solution of longifolene (210 g) in bromotrichloromethane (917 g) is heated under reflux, in a pure nitrogen atmosphere, for 31 hr, with a 200-W Mazda "infrared" lamp (Model 124-O). By distillation, the excess bromotrichloromethane is recovered at atmospheric pressure; by reduced pressure distillation (20 Torr), some longifolene (100 g) is then recovered. The brown, viscous residue is dissolved in petroleum ether (30–60°) and cooled overnight at −20°. The large prismatic crystals of the adduct are filtered and recrystallized from methanol to give 84.7 g (20% overall; 40% based on reacted longifolene) of colorless crystals of **4** (Z = CH_2CCl_3).

Methyl 3α-bromo(7β*H*)longifolate (**4b**) (Z = CO_2CH_3), 3α-bromo-15-chloromethyl(7β*H*)longifolane (**4c**) (Z = C≡CCl), 3α-bromo-(7β*H*)longifolol (**4f**) (Z = CH_2OH), and 3α-bromo(7β*H*)longifolane (**4h**) (Z = CH_3) were prepared as described previously.[11]

3α-Bromo(7β*H*)longifonitrile (4a) (Z = CN). The corresponding acid **4** (Z = CO_2H) (0.5 g), dissolved in anhydrous benzene (15 ml), was treated with thionyl chloride (0.35 ml) and heated under reflux. After 3 hr, the reaction mixture was evaporated under reduced pressure, dissolved in anhydrous benzene, and saturated with dry ammonia. After evaporation to dryness under reduced pressure, anhydrous ether was added; the solution was pipetted from the precipitated ammonium chloride, and added to a solution of phosphorus oxychloride (2 ml) and pyridine (2.5 ml) in anhydrous ether (5 ml). The mixture was heated under reflux for 4 hr, cooled in an ice bath, and carefully treated with water. The usual work-up gave a crude product, which was chromatographed on silica gel. Elution with ether (15%) in petroleum ether gave the nitrile **4a** (Z = CN) (0.265 g; 55%), which was recrystallized from petroleum ether.

3α,15-Dibromo(7β*H*)longifolane (4d) (Z = CH_2Br). 3α-Bromolongifolol tosylate **4** (Z = CH_2OTs) (0.24 g) was dissolved in 1,2-

Table V

Products	Nmr, J in Hz (CCl_4)	Ir, cm^{-1} (smear)	*Anal.*, %, and mass spectra Calcd	 Found
	CH_3-14, 61 (s) CH_3—C=, 102.5 (s) CH_2=C—, 279 (s) -CO_2CH_3, 211 (s) H-7, 160 (d, J = 5)	1645 ($\nu_{C=C}$) 890 (δ $\overset{H}{\underset{H}{}}$>C=C) 1740 ($\nu_{C=O}$)	$C_{16}H_{24}O_2$ C, 77.37; H, 9.74	C, 77.61; H, 9.87
	CH_3-14, 61 (s) $CH_3CH(CH_3)$, 60 (d, J = 6) -CH=C-, 309 (m) -CO_2CH_3, 211 (s) H-7, 150 (d, J = 5)			
	CH_3-14, 60 (s) $CH_3C(CH_3)O$– 67 (s) -CO_2CH_3, 212 (s) H-7, 149 (d, J = 5)	3440–3480 (ν_{OH}) 1735 ($\nu_{C=O}$)	$C_{16}H_{26}O_3$ M^+ = 266	M^+ = 266 $(M - H_2O)^+$ = 248
	CH_3-14, 70 (s) CH_3—C=, 102 (s) CH_2=C—, 280 (s)	2240 ($\nu_{C\equiv N}$) 1645 ($\nu_{C=C}$) 885 (δ) $\overset{H}{\underset{H}{}}$>C=C)	$C_{15}H_{21}N$ C, 83.67; H, 9.83; N, 6.51	C, 83.31; H, 10.07; N, 6.77
	CH_3-14, 70 (s) $CH_3C(CH_3)$, 72 (d, J= 7) -CH=C-, 312 (m)			
 $[\alpha]_D$ +36°	CH_3-14, 52.5 (s) CH_3-12, 56 (s) CH_3-13, 56 (s) CH_3—C=, 95.5 (d, J = 7) -CH=C-, 293 (q, J = 7)	1670 ($\nu_{C=C}$)	C, 88.00; H, 12.00 M^+ = 218	$C_{16}H_{26}$ C, 88.04; H, 12.22 $C_{16}H_{26}$ M^+ = 218 $(M - CH_3)^+$ = 203 $(M - C_2H_5)^+$ = 189

dimethoxyethane (10 ml) and lithium bromide (0.475 g) was added. After 15 hr of reflux, the mixture was evaporated to dryness under reduced pressure. The crude product (0.185 g) was shown (tlc, nmr) to be a mixture of two substances. One is the expected dibromide **4d** (60% from nmr) and the other is 3α-bromolongifolene,[13] the product of elimination of the tosylate. The pure dibromide is obtained with some difficulty by repeated crystallizations from petroleum ether at −20°.

3α-Bromo-15-iodo(7β*H*)longifolane (4e) (Z = CH_2I). A solution of the tosylate **4** (Z = CH_2OTs) (0.257 g) in 1,2-dimethoxyethane (7 ml) is treated at reflux with lithium iodide (0.8 g, washed with benzene and dried). After 6 hr, the mixture is cooled, a few crystals of sodium hydrogen carbonate are added, and the solvent is removed under reduced pressure. The residue is leached with petroleum ether to give a crude, brownish product, which is *immediately* filtered over *neutral* alumina (Woelm, activity III). The bromo-iodide **4f** is eluted with petroleum ether to give colorless crystals (0.157 g; 68%), recrystallized from petroleum ether at −20°.

3α-Bromo-15-methoxy(17β*H*)longifolane (4g) (Z = CH_2OCH_3). This procedure was inspired by Diner, Sweet, and Brown.[42] A suspension of sodium hydride in mineral oil is diluted with 1,2-dimethoxyethane and centrifuged, and the solid is washed several times with the same solvent. A solution of the alcohol **4f** (Z = CH_2OH) (0.5 g) in 1,2-dimethoxyethane (4 ml) is cooled in an ice bath, and treated with an excess of sodium hydride. Methyl iodide (0.9 ml) is then added. After 6 hr, water is cautiously added, and most of the solvent is evaporated under reduced pressure. The residue is extracted with ether to give a crude product (0.505 g), the nmr spectrum of which shows that it contains essentially pure **4g** (96%). This is filtered over silica gel; with 4% ether-petroleum ether is eluted the pure ether **4g**, as a colorless liquid. This is submitted to short-path distillation (50°, 10^{-2} Torr).

3α-Bromo-15-methyl(7β*H*)longifolane (4i) (Z = CH_2CH_3). 3α-Bromo-15-chloromethyn(7β*H*)longifolane (**4**) (Z = C≡CCl) (0.5 g) is hydrogenated at atmospheric pressure in absolute ethanol (125 ml) in the presence of 5% palladium on charcoal (0.15 g). After saturation, a few crystals of sodium hydrogen carbonate are added, and the solvent is evaporated under reduced pressure *at room temperature*. The residue is extracted with ether to give a crude product (0.420 g), crystallizing at −20° (90%). This substance, very sensitive to solvolysis, cannot be heated in a polar solvent, and is very soluble in any solvent. With some difficulty, it has been recrystallized from methanol by cooling down to −20°.

Kinetics. For each run, usually nine adequately spaced points were chosen for the titrations. In the solvolysis at 60°, at least two completely independent runs were performed. Good or excellent first-order rate laws were usually observed by using the experimental "infinite" time value; in two cases, where side reactions could not be prevented, they were taken into account as mentioned in Table I.

Ethanol (80%) was obtained by adding 1 vol of distilled water, at 20°, to 4 vol of freshly distilled absolute ethanol. Two batches were prepared at a 6-month's interval; several kinetic runs were run in duplication in these two solvents, with good coincidence in the numerical results obtained.

The substance studied, after thorough pulverizing in an agate mortar, was weighed in a 50-ml volumetric flask (0.5 or 0.25 mmol, weighed to 0.1 mg), and quickly dissolved by shaking at room temperature. Nine predrawn test tubes are each filled with 5–6 ml of the solution, and are sealed either as such or (without any difference in the results) after displacing air with argon. The sealed tubes are placed in the thermostat (Colora ultrathermostat, ±0.1°). As soon as the temperature of the bath is restored, one tube is taken out and titrated. Seven other tubes are titrated at appropriately spaced time intervals, to cover at least 80% of the total reaction. The ninth tube is left in the thermostat during at least 10 times the half-life of solvolysis, to measure the "experimental value for infinite time." Each titration is performed on exactly 5 ml of the solvolyzed solution with a 0.01 *M* sodium methoxide solution in methanol, standardized with potassium hydrogen phthalate.

Indicator. The indicator was *p*-bromothymol blue, turning to blue. We have used a Manostat-Greiner micrometric buret, reading to 10^{-3} ml, with the capillary tip immersed in the solution.

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(42) U. E. Diner, F. Sweet, and R. K. Brown, *Can. J. Chem.*, **44**, 1591 (1966).

Analyses of solvolysis products have been run on 0.1 *M* solutions heated during some ten half-lives in a stoppered flask, in the presence of more than 1 equiv of sodium acetate or sodium hydrogen carbonate to minimize secondary, acid-catalyzed reactions.

Table V summarizes the physical data of the solvolysis products.

Solvolysis of 4b ($Z = CO_2CH_3$). In 20 ml of 80% ethanol was dissolved 0.4 g of the bromo ester **4b** ($Z = CO_2CH_3$). Sodium acetate (0.24 g) was added. The sealed ampoule was heated at 110° for 5 hr. The solvent was removed under reduced pressure and the product isolated in the usual way. Of the colorless, viscous oil obtained (0.295 g) one part (0.245 g) was chromatographed over silica gel (10 g; dry column technique). Four fractions homogeneous in tlc have been obtained, of which two have been identified.

Fraction 1 (0.10 g) is eluted with 5% ether in petroleum ether. It is a *mixture* of the two ring-contracted esters obtained previously by acetolysis of **4b**[11] (*cf.* Figure 2). Quantitative evaluation of the 100-MHz nmr spectrum of the *crude reaction product* shows that this mixture of two esters makes up to 45–50% total product.

Fraction 4 (0.025 g) is eluted with 25% ether in petroleum ether. It is the methyl ester of a hydroxy acid obtained previously by saponification of the acetate[11] described in Figure 2 (route a). Methylation of this hydroxy acid with diazomethane gave an authentic comparison material.

In the present case, we have not been able to develop conditions for vpc analysis of the reaction mixture, and have not been able to deduce plausible structures for the other two products isolated.

Solvolysis of 4a (Z = CN). The same procedure was used with the bromonitrile **4a** (0.10 g). The crude product (0.073 g) gave an nmr spectrum compatible with a 1:1 mixture of the two ring-contracted nitriles described in Table V, and forming at least 70% total reaction product. The crude product (0.073 g) was chromatographed on silica gel. Ether (10%) in petroleum ether eluted the mixture of the two nitriles (0.053 g), homogeneous in tlc.

Solvolysis of 4h ($Z = CH_3$). 3α-Bromolongifolane **4h** ($Z = CH_3$) (0.057 g) was heated in 80% ethanol at reflux during 6 hr, in the presence of sodium hydrogen carbonate (0.10 g). The solvent was removed under reduced pressure and the product was extracted in the usual way. The crude oily product (0.032 g) was analyzed by vpc (140°, 5% OV-17 on Aeropak). Beside longifolene (80%), four more polar products are present (*ca.* 5% each); they appear to be alcohols or ethers, as judged by their retention times. This evaluation is confirmed by nmr. Longifolene had already been isolated from a similar reaction.[11]

Solvolysis of 4i ($Z = CH_2CH_3$). The bromide **4i** ($Z = CH_2CH_3$) (0.070 g) was treated by the preceding procedure. The crude product, by vpc in the same conditions, is shown to contain one major product (90%) and three more polar products (2, 5, and 3%). This is confirmed by nmr. The major product is purified by chromatography on silica gel, to give methyl-15 longifolene.

Free-Radical Hydrogen Abstraction from Polycyclic Aliphatic Hydrocarbons[1]

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Contribution from the Department of Chemistry, Oregon State University, Corvallis, Oregon 97331. *Received August 26, 1970*

Abstract: Six polycyclic aliphatic hydrocarbons were allowed to react with the trichloromethyl radical photolytically generated from bromotrichloromethane at 40°. Relative rates of hydrogen abstraction were correlated with a computer analysis of the change in strain energy in going from the ground state to the intermediate. A good correlation between the log of the relative rates and the calculated changes in strain energy was obtained.

The problem of bridgehead free-radical reactivity has been under investigation for the last 30 years. Recent work has engendered conflicting data concerning the relative stabilities of certain of these species. Applequist and Kaplan studied the decarbonylation of polycyclic aldehydes.[3] They found that the 1-adamantyl radical was formed 2.50 times as fast as the *tert*-butyl radical indicating that the bridgehead adamantyl radical is the more stable species. In the decomposition of *tert*-butyl peresters Fort and Franklin and Lorand and coworkers[4] observed that the 1-adamantyl radical is formed about 1.2 times as fast as the *tert*-butyl radical indicating both radicals to be of roughly equivalent stability. Chick and Ong[5] found that the 1-adamantyl radical is formed only 0.137 times as rapidly as the *tert*-butyl radical in hydrogen abstraction from the appropriate alkyl benzyl ethers. This result stands in marked contrast to the other examples cited.

The mechanism and thermochemistry of hydrogen abstraction by the trichloromethyl radical is well documented.[6–8] Since the abstraction of the alkyl hydrogen is endothermic it follows by the Hammond postulate[9] that the intermediate alkyl radical resembles the transition state. It was felt that an examination of the relative rates of hydrogen abstraction from a series of saturated polycyclic systems might yield insight as to the comparative stabilities of bridgehead radicals. Unlike the studies of Applequist and Kaplan[3] or Chick and Ong,[5] relative rates may be directly obtained. A problem associated with both systems involves the expression of the rates of radical formation with regard to some common reaction, the rate of which is assumed independent of structure. The validity of this assumption, however, is open to question.[4] A serious problem is also present in the studies on perester decomposition. It has recently been shown that loss of carbon dioxide from the possible intermediate acyloxy radical may be

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(1) Presented at the Northwest Regional Meeting of the American Chemical Society, June 18, 1970.

(2) (a) Taken in part from the M.S. Thesis of V. R. Koch. (b) Alfred P. Sloan Fellow (1969–1971).

(3) D. E. Applequist and L. Kaplan, *J. Amer. Chem. Soc.*, **87**, 2194 (1965).

(4) (a) R. C. Fort, Jr., and R. E. Franklin, *ibid.*, **90**, 5267 (1968); (b) John Lorand, S. D. Chodroff, and R. W. Walker, *ibid.*, **90**, 5266 (1968).

(5) W. H. Chick and S. H. Ong, *Chem. Commun.*, 216 (1969).

(6) B. P. McGrath and J. M. Tedder, *Bull. Soc. Chim. Belg.*, **71**, 772 (1962).

(7) E. S. Huyser, *J. Amer. Chem. Soc.*, **82**, 391 (1960).

(8) G. J. Gleicher, *J. Org. Chem.*, **33**, 332 (1968).

(9) G. S. Hammond, *J. Amer. Chem. Soc.*, **77**, 334 (1955).