

parison of the abundance of corresponding ^{18}O and ^{16}O components. The enriched water contained 68.68 ± 0.44 atom % ^{18}O , and the sample of alcohol **22** contained 69.94 ± 0.49 atom % ^{18}O . Thus the incorporation of ^{18}O in product **22** on solvolysis of triflate **25** was $101.8 \pm 1.4\%$.

Acknowledgments. We are grateful for helpful discussions with Professors J. E. Leffler, R. E. Robertson, and P. von R. Schleyer, and for financial support from the National Institutes of Health.

Steric Assistance in the Solvolysis of 2-Alkyl-2-adamantyl *p*-Nitrobenzoates¹

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Abstract: In order to estimate the relative importance of alkyl inductive and steric effects in the 2-adamantyl system, rates of solvolysis of a series of 2-alkyl-2-adamantyl *p*-nitrobenzoates were determined in 80% aqueous acetone. The relative first-order rate constants at 25° were: CH_3 , 1.0; C_2H_5 , 7.7; $\text{CH}_2\text{C}(\text{CH}_3)_3$, 10.0; *i*- C_3H_7 , 33.5; *t*- C_4H_9 , 225,000. The solvolysis products are the unrearranged alcohols and exocyclic olefins, except in the case of 2-*tert*-butyl-2-adamantyl *p*-nitrobenzoate where the methyl-shifted olefin, 2-methyl-2-(2'-isopropenyl)-adamantane, was formed in addition to the unrearranged alcohol. Conformational analysis calculations were performed and the relative strain energy differences between the hydrocarbon and the corresponding cation were calculated (kcal/mol) to be: CH_3 , 0.0; C_2H_5 , 0.5; $\text{CH}_2\text{C}(\text{CH}_3)_3$, 1.4; *i*- C_3H_7 , 1.8; *t*- C_4H_9 , 4.5. A good correlation of the hydrocarbon-cation strain energy change *vs.* the log of the rate of solvolysis is observed, the average deviation in rates being $10^{\pm 0.3}$. Steric effects are shown to play the dominant role in the 2-alkyl-2-adamantyl system. The question of steric assistance in the observed 2-adamantyl $\alpha\text{-CH}_3/\text{H}$ ratio, 10^8 , is also considered. No significant steric acceleration is indicated; the observed $\alpha\text{-CH}_3/\text{H}$ rate ratio originates almost entirely from electronic considerations.

Very recently, the 2-adamantyl system has been used as a model to approximate the behavior of an idealized secondary substrate that is resistant to changes in solvent nucleophilicity in solvolytic reactions.^{3,4} That this system does, to a remarkable degree, approximate such "limiting" (carbonium ion-like) behavior has been attributed to the inhibition of backside approach of nucleophilic solvent by the nonbonded repulsive interactions with the methylene hydrogens in the adamantane structure.

One of the characteristics displayed by the 2-adamantyl system is the enormous solvolytic rate enhancement observed when the methine hydrogen at C-2 is replaced by a methyl group. Rate enhancement factors for the solvolysis of bromides **1-Br** and **2-Br** were $10^{7.5}$ (25°, in 80% aqueous ethanol) and $10^{8.1}$ (25°, acetolysis).^{3b} Under the same conditions, the rate ratio *tert*-butyl bromide (*t*-BuBr)/isopropyl bromide (*i*-PrBr) is only $10^{3.7}$. The rate ratio **1-Br**/*i*-PrBr of 1.6×10^{-3} is much less than the 9.7 rate ratio for **2-Br**/*t*-BuBr. These data suggested that isopropyl bromide alone of the four bromides was behaving exceptionally; isopropyl bromide,

unlike 2-adamantyl bromide, benefits from considerable nucleophilic solvent assistance. The value 10^8 was therefore assigned as the new provisional limiting value of the α -methyl/hydrogen rate ratio in the absence of anchimeric and solvent assistance.

If the value of 10^8 for the limiting α -methyl/hydrogen rate ratio is to have any generality for the interpretation of solvolytic behavior, electronic stabilization must be the principle cause and not relief of ground-state steric strain. We wished to see whether or not this was true. It is known that 2-aryl-2-adamantyl substrates are quite sensitive to aryl substituent effects,⁵ but no information was available concerning the relative importance of alkyl inductive and steric effects in 2-alkyl-2-adamantyl substrates.

In order to determine the importance of these effects, a series of 2-alkyl-2-adamantyl *p*-nitrobenzoates was prepared and the rates of solvolysis were determined. Since specific nucleophilic solvent participation should not be present in any of these compounds, observed reactivity differences should only reflect inductive and "B-strain"^{6,7} effects.

Results

2-Alkyl-2-adamantanols were prepared by addition of the appropriate alkyl Grignard or lithium compound to adamantanone. Only 2-methyl- (2-OH) and 2-neopentyl-2-adamantanol (4-OH) could be prepared in good yield (~90%) by the Grignard addition; 2-ethyl-

(5) H. Tanida and T. Tsushima, *J. Amer. Chem. Soc.*, **92**, 3397 (1970).

(6) P. D. Bartlett and T. T. Tidwell, *ibid.*, **90**, 4421 (1968), and references cited therein.

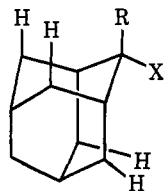
(7) H. C. Brown and R. S. Fletcher, *ibid.*, **71**, 1845 (1949); **73**, 1317 (1951), and other papers in this series.

(1) Presented, in part, at the 157th National Meeting of the American Chemical Society, Minneapolis, Minn., April 1969, Abstract No. ORGN-133, and at the Sixth Middle Atlantic Regional Meeting of the American Chemical Society, Baltimore, Md., Feb 1971, Abstract P-70.

(2) National Institutes of Health Postdoctoral Fellow, 1967-1969.

(3) (a) J. L. Fry, C. J. Lancelot, L. K. M. Lam, J. M. Harris, R. C. Bingham, D. J. Raber, R. E. Hall, and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **92**, 2538 (1970); (b) J. L. Fry, J. M. Harris, R. C. Bingham, and P. v. R. Schleyer, *ibid.*, **92**, 2540 (1970); (c) P. v. R. Schleyer, J. L. Fry, L. K. M. Lam, and C. J. Lancelot, *ibid.*, **92**, 2542 (1970); (d) S. H. Liggero, J. J. Harper, P. v. R. Schleyer, A. P. Krapcho, and D. E. Horn, *ibid.*, **92**, 3789 (1970); (e) J. M. Harris, D. J. Raber, R. E. Hall, and P. v. R. Schleyer, *ibid.*, **92**, 5729 (1970).

(4) J. A. Bone and M. C. Whiting, *Chem. Commun.*, 115 (1970).



- 1-X; R = H
 2-X; R = CH₃
 3-X; R = C₂H₅
 4-X; R = CH₂C(CH₃)₃
 5-X; R = *i*-C₃H₇
 6-X; R = *t*-C₄H₉

(3-OH), 2-isopropyl- (5-OH), and even the highly strained 2-*tert*-butyl-2-adamantanol (6-OH)⁸ were alkyl-lithium addition products.

Solvolysis rates of the 2-alkyl-2-adamantyl *p*-nitrobenzoates (2-OPNB–6-OPNB), prepared by the alkoxide method,^{6,10} were measured in 80% (v/v) acetone titrimetrically and conductometrically (Table I). In-

Table I. Measured First-Order Rate Constants for 2-Alkyl-2-adamantyl *p*-Nitrobenzoates in 80% Aqueous Acetone (by Volume)

Compd	Temp, °C	k , sec ⁻¹ ^a	k_{rel} 25°	ΔH^\ddagger , kcal/mol	ΔS^\ddagger , eu
<i>t</i> -BuOPNB	25.0	7.45×10^{-11} ^b	1.0	29.2	-7.1
2-OPNB	124.8	6.88×10^{-5}			
	100.0	5.07×10^{-6}			
3-OPNB	25.0	1.43×10^{-10} ^c	2.0	30.2	-2.2
	125.0	2.25×10^{-4}			
	100.1	1.96×10^{-5}			
4-OPNB	25.0	1.14×10^{-9} ^c	15.4	28.1	-5.3
	101.0	3.92×10^{-5}			
	84.4	6.14×10^{-6}			
5-OPNB	25.0	1.49×10^{-9} ^c	20.0	29.0	-1.6
	100.1	8.56×10^{-5}			
	76.1	5.95×10^{-6}			
6-OPNB	25.0	4.97×10^{-9} ^c	67.0	28.1	-2.4
	75.4	7.77×10^{-3} ^d			
	50.1	6.31×10^{-4} ^d			
	25.0	3.42×10^{-5} ^c	450,000	21.6	-6.5

^a Determined titrimetrically unless otherwise noted. Average of duplicate determinations. In no case did the average deviation exceed 5%. ^b Reference 11. ^c Calculated from other temperatures. ^d Determined conductometrically.

cluded in this table are comparison data for *t*-Bu-OPNB.¹¹

For the product studies, *p*-nitrobenzoates, 2-OPNB–6-OPNB, were heated for 6 or more half-lives in 80% aqueous acetone containing *ca.* 50 mol % excess 2,6-lutidine buffer. Since the most highly reactive 6-OPNB gave the same products in the absence as in the presence of base, it was assumed that the products were at least largely those of kinetic control. The relative yields of products identified by comparison of glc retention times with those of authentic samples and by their nmr and ir spectra are shown in Chart I.

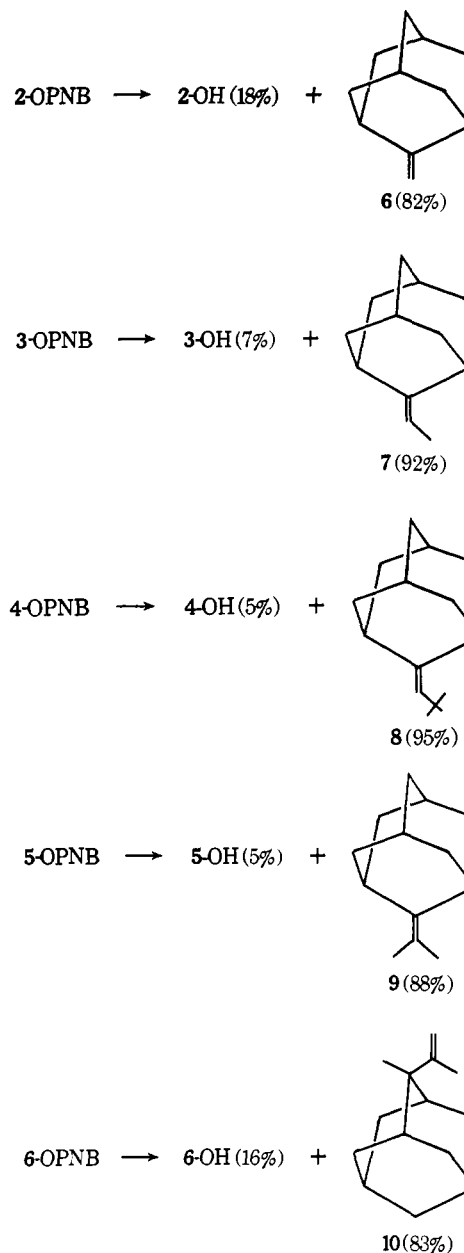
(8) 2-*tert*-Butyladamantane, the first cyclohexyl system possessing a locked axial *tert*-butyl group, was prepared with much more difficulty than 6-OH.⁹

(9) C. W. Woodworth, V. Buss, and P. v. R. Schleyer, *Chem. Commun.*, 569 (1968).

(10) H. C. Brown, R. Bernheimer, C. J. Kim, and S. E. Scheppele, *J. Amer. Chem. Soc.*, **89**, 370 (1967).

(11) H. C. Brown and W. C. Dickason, *ibid.*, **91**, 1226 (1969).

Chart I. Products from 80% Aqueous Acetone Solvolysis of 2-Alkyl-2-adamantyl *p*-Nitrobenzoates (Relative Yields in Parentheses)



In several cases small amounts of unidentified products also were formed (see Experimental Section).

Discussion

Origin of the Rate Enhancements Observed. While the solvolysis rate of 2-methyl-2-adamantyl *p*-nitrobenzoate (2-OPNB) was only about two times faster (25°) than that of *t*-BuOPNB, the other 2-alkyl-2-adamantyl *p*-nitrobenzoates (3-OPNB, 4-OPNB, 5-OPNB, and 6-OPNB) reacted more rapidly. The 2-*tert*-butyl derivative (6-OPNB) showed remarkably large acceleration; its rate was 460,000 times faster than *tert*-butyl *p*-nitrobenzoate. 6-OPNB is one of the fastest reacting aliphatic tertiary systems known.¹²

(12) Previously cited rate enhancements relative to *tert*-butyl *p*-nitrobenzoate at 25°: (a) 2,6,6-trimethyl-*exo*-norbornyl *p*-nitrobenzoate, 97,500: S. Ikegami, D. L. Vander Jagt, and H. C. Brown, *ibid.*, **90**, 7124 (1968); (b) *tert*-butylideneopentylcarbinyl *p*-nitrobenzoate, 129,500, ref 6; (c) *trans,trans,cis*-perhydro-9 β -phenalenol, 203,000, and *cis,cis,cis*-perhydro-9 β -phenalenol, 2,030,000: ref 11.

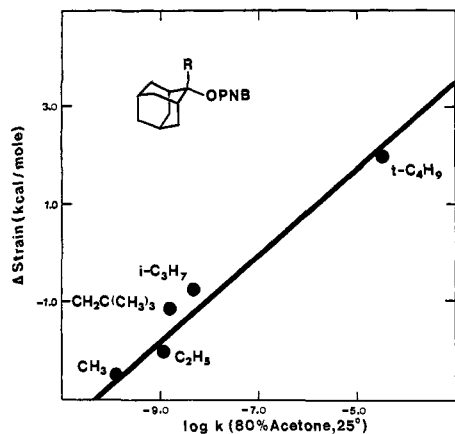
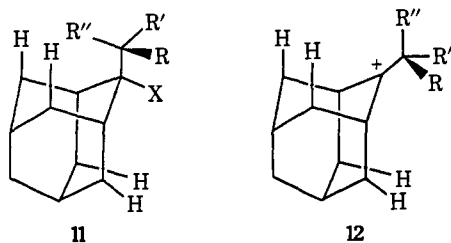


Figure 1. Calculated hydrocarbon-cation strain energy differences (Δ strain) plotted against log of the experimental rate constants (80% acetone, 25°) for a series of 2-alkyl-2-adamantyl *p*-nitrobenzoates; least-squares fit: $\log k = 1.23\Delta$ strain - 6.93.

While inductive or hyperconjugative¹³ effects might be expected to produce modest rate enhancements along the series methyl to *tert*-butyl the very large accelerations for 6-OPNB obviously must be due to relief of steric strain; this factor undoubtedly is present in the lower members of the series as well.

The origin of possible steric effects in the 2-alkyl-2-adamantyl system is illustrated by **11** and **12**. In the



tetrahedral ground-state **11**, the alkyl substituent is locked into an axial position on an inflexible chair-form cyclohexane ring. Rehybridization of C₂ in the carbocation ion **12** allows the alkyl group to assume a more favorable conformation in which energetically unfavorable steric interactions are minimized. The larger the alkyl substituent, the greater the ground-state strain, and the faster the substrate will ionize. Such B-strain effects are well documented.^{6,7,14} Thus, inductive, hyperconjugative and steric effects along the series methyl to *tert*-butyl should operate in the same direction: to increase the rate. The *maximum* acceleration due to inductive-hyperconjugative effects can readily be evaluated by using the familiar Taft-Hammett treatment.¹⁵ With $\rho^* = 3.3$ (for tertiary halides in 80% ethanol)¹⁶ and the known σ^* alkyl group values relative rates for a series of compounds, R'₂RCX, vary over a power of ten from R = CH₃ to R = *t*-C₄H₉ (Table II). However, the magnitude of Streitwieser's ρ^* is determined largely by compounds with electron-withdrawing groups; for the simplest tertiary series, R(CH₃)₂CCl, little variation in rate is found (Table II). The relative

(13) L. Radom, J. A. Pople, V. Buss, and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **92**, 6380 (1970).

(14) E. L. Eliel, "Stereochemistry of Carbon Compounds," McGraw-Hill, New York, N. Y., 1962, p 379.

(15) R. W. Taft, Jr., *J. Amer. Chem. Soc.*, **74**, 2729, 3120 (1952).

(16) A. Streitwieser, Jr., "Solvolytic Displacement Reactions," McGraw-Hill, New York, N. Y., 1962, Table 52.

Table II. Analysis of Solvolysis Rates of *tert*-Alkyl Chlorides, R(CH₃)₂CCl^a

R	$k_{\text{rel}}(80\% \text{ EtOH}, 25^\circ)$	k_{calcd}^b	k^c
CH ₃	1.0	1.0	1.0
C ₂ H ₅	1.6	2.0	7.2
CH ₂ C(CH ₃) ₃	21.6	3.5	10.0
<i>i</i> -C ₃ H ₇	0.9	4.5	33.5
<i>t</i> -C ₄ H ₉	1.3	10.0	225,000

^a Data from ref 16. ^b Rates calculated from Taft $\sigma^*\rho^*$ treatment with $\rho^* = 3.29$. ^c 2-R-2-adamantyl *p*-nitrobenzoates, 80% acetone, 25°; this work.

rate enhancements for 3-OPNB-6-OPNB in Table I are much larger even than the maximum Taft-Hammett values. This shows clearly the operation of steric effects, even with the ethyl and isopropyl derivatives, 3-OPNB and 5-OPNB.

To evaluate the magnitude of these steric effects, conformational analysis calculations have been performed. These calculations involve an application by computer¹⁷⁻¹⁹ of Westheimer's²⁰ classical treatment for the quantitative determination of steric effects operative in molecules. Steric effects are considered to be the sum of various strain-producing mechanisms assumed to be independent, as expressed in energy terms by eq 1.

$$E(\text{total strain}) = E(\text{bond stretch strain}) +$$

$$E(\text{angle bend strain}) +$$

$$E(\text{torsional strain}) + E(\text{nonbonded strain}) \quad (1)$$

Ideally, the variation in the rates of solvolysis can be assessed by evaluating the change in strain in going from the ground to the transition state. In our earlier work simplifications were made: the ground state was approximated by the parent hydrocarbon and the transition state by the corresponding carbonium ion.²¹⁻²³ This type of treatment has already been successfully applied to the correlation of rates of carbonium ion reactivities of 16 bridgehead systems which vary by more than 18 powers of ten with the changes in strain energy in going from ground to transition state.²² If steric effects are indeed playing an important role in the 2-alkyl-2-adamantyl system, one would expect a similar correlation of the rates with the changes in strain energy.

The results of our calculations are summarized in Table III. Figure 1 demonstrates the very good correlation between the calculated hydrocarbon-cation

(17) Review: J. E. Williams, Jr., P. J. Stang, and P. v. R. Schleyer, *Annu. Rev. Phys. Chem.*, **19**, 531 (1968).

(18) K. B. Wiberg, *J. Amer. Chem. Soc.*, **87**, 1070 (1965); H. A. Harris, Ph.D. Thesis, Yale University, 1966.

(19) (a) N. L. Allinger, M. A. Miller, F. A. VanCatledge, and J. A. Hirsch, *J. Amer. Chem. Soc.*, **89**, 4345 (1967); (b) N. L. Allinger, J. A. Hirsch, M. A. Miller, I. J. Tyminski, and F. A. VanCatledge, *ibid.*, **90**, 1199 (1968); (c) N. L. Allinger, M. T. Tribble, M. A. Miller, and D. H. Wertz, *ibid.*, **93**, 1637 (1971).

(20) F. H. Westheimer in "Steric Effects in Organic Chemistry," M. S. Newman, Ed., Wiley, New York, N. Y., 1956, Chapter 12.

(21) G. J. Gleicher and P. v. R. Schleyer, *J. Amer. Chem. Soc.*, **89**, 582 (1967).

(22) R. C. Bingham and P. v. R. Schleyer, *ibid.*, **93**, 3189 (1971).

(23) R. C. Bingham, W. F. Sliwinski, and P. v. R. Schleyer, *ibid.*, **92**, 3471 (1970); S. A. Sherrod, R. G. Bergman, G. J. Gleicher, and D. Morris, *ibid.*, **92**, 3469 (1970); P. v. R. Schleyer, P. R. Isele, and R. C. Bingham, *J. Org. Chem.*, **33**, 1239 (1968); W. G. Dauben and C. D. Poulter, *ibid.*, **33**, 1237 (1968); R. C. Bingham and P. v. R. Schleyer, *Tetrahedron Lett.*, **27** (1971); V. R. Koch and G. J. Gleicher, *J. Amer. Chem. Soc.*, **93**, 1657 (1971); A. Karim, M. A. McKervey, E. M. Engler, and P. v. R. Schleyer, *Tetrahedron Lett.*, 3987 (1971).

Table III. Calculated Strain Energies for 2-Alkyl-2-adamantanes

Alkyl group	Hydrocarbon, ^a kcal/mol	Cation strain, ^a kcal/mol	Δ strain ^b
H	6.5	9.5	-3.0
CH ₃	7.2	9.7	-2.5
C ₂ H ₅	7.5	9.5	-2.0
CH ₂ C(CH ₃) ₃	10.0	11.1	-1.1
<i>i</i> -C ₃ H ₇	8.5	9.2	-0.7
<i>t</i> -C ₄ H ₉	13.1	11.1	+2.0

^a See Table IV for potential functions and parameters employed in these strain calculations. ^b Difference in strain between columns 1 and 2.

strain differences (column 4, Table III) and the log of the rates of solvolysis of 2-OPNB-6-OPNB (data from Table I). This correlation supports our contention that steric effects play a major role in the observed rate accelerations. The average deviation of the calculated rates from the experimental values was $10^{\pm 0.3}$. This deviation is extremely creditable in view of the numerous simplifying assumptions which were made.^{21, 22} In particular, steric effects involving the leaving groups were completely neglected.²² These steric effects cannot be negligible in magnitude, since the leaving groups are axial to one of the cyclohexane rings comprising the adamantane skeleton and interactions with the 2-alkyl groups are present as well. Nevertheless, our approximation is justified by the expectations that leaving group steric effects will be constant or proportional over the series examined. The good correlation actually obtained (Figure 1) supports this assumption.

Analysis of the individual strain component terms of eq 1 shows that the rate enhancements in 3-OPNB, 4-OPNB, and 5-OPNB, relative to 2-OPNB, arise mainly from relief of nonbonded interactions. Repulsive interactions due to the methyl group (R'' in 11) lying over the cyclohexane ring in 6-H produce serious distortions in the valence angles; relief of both nonbonded and angle strains thus in going to the 6 cation (12, R = R' = R'' = CH₃) produces the large rate enhancement observed.

One further possible source of the observed rate enhancements—participation—needs to be considered. Participation is not expected in the methyl derivative 2 and is highly unlikely in 3 and 4, where hydrogen migration would convert tertiary to secondary cations. Bartlett and Tidwell⁶ have presented cogent arguments against such hydrogen participation in crowded neopentyl systems. Thus, only hydrogen participation in 5-OPNB and methyl participation in 6-OPNB would seem to require consideration.

However, the observation of appreciable amounts of unrearranged products from 5-OPNB and 6-OPNB argues against participation as the major source of rate enhancement in these compounds. If strain is relieved due to participation, then one would not expect any products of unrearranged structure when the rate enhancements observed are large.

We conclude that the principle cause of the rate enhancements observed with 3-OPNB-6-OPNB is relief of ground-state steric strain. Inductive and hyperconjugative effects operate in the same direction, but play a more minor role. Participation, expected only in

5-OPNB and 6-OPNB, does not appear to be important, but some contribution cannot be ruled out.

The 2-Adamantyl α -CH₃/H Ratio. The very large rate difference produced by α -methyl substitution in the 2-adamantyl system—about 10^8 —has been ascribed to the absence of significant nucleophilic solvent assistance in both the secondary (1-Br) and tertiary (2-Br) compounds.^{3b} We have proposed that this α -CH₃/H ratio, 10^8 , be adopted as a new limiting value against which values for other systems be compared.^{3b} However, another factor—steric assistance to ionization in 2-Br—needs to be considered as a possible contributing factor to the high α -CH₃/H ratio. We have already argued that this factor should be small.^{3b} Detailed justification for this contention is presented here.

The secondary (1) and tertiary (2) 2-adamantyl systems differ by a methyl group which lies axial to one of the cyclohexane rings. Because of the heightened rigidity of the adamantane system, such an axial methyl group would be expected to introduce somewhat more strain than usual; a value of 2.7 kcal/mol has been estimated experimentally.²⁴ If *all* of this excess strain were relieved on ionization of 2, a steric acceleration of 10^2 at 25° would result. We believe the actual acceleration is considerably less than this, since the amount of steric strain relief in going from ground to transition state should only be a fraction of the total amount of ground-state strain present.

On an absolute basis the rates of solvolysis of 2-methyl-2-adamantyl derivatives 2 do not indicate any marked acceleration, being only slightly faster than those for corresponding *tert*-butyl derivatives (*p*-nitrobenzoate ratio = 2 at 25° (Table I); bromide ratio = 10 at 25°^{3b}). We have already argued that these small 2-methyl-2-adamantyl/*tert*-butyl ratios can be attributed to the inductive-hyperconjugative stabilization afforded by the greater degree of chain branching.^{3b} Another example illustrating the effect of chain branching can be cited: methyldiisopropylcarbinyl chloride solvolyses 5.2 times faster than methyldiethylcarbinyl chloride (80% ethanol, 25°).⁶

Another comparison also indicates a low degree of steric acceleration in the 2-methyl-2-adamantyl system 2. 2-Cl, possessing *both* axial halide and methyl groups, solvolyses 22.5 times faster than 1-methylcyclohexyl chloride (80% ethanol, 25°),²⁵ which can leave only one group (presumably the leaving group) axial. After correcting for the chain branching effect (22.5/5.2), only a ratio of 4.3 remains. This ratio, corresponding to an activation free energy of 0.9 kcal/mol, can reasonably be ascribed to the methyl steric acceleration in 2-Cl.

This estimate is supported by our strain calculations on 1 and 2 (Table III). Strain relief in going to the carbonium ion is only 0.5 kcal/mole greater for the methyl system 2 than for the secondary derivative 1. By use of the least-squares fit of Figure 1, a steric acceleration factor of 4 can be calculated for 2.²⁶ Thus no significant steric acceleration associated with the tertiary substrate 2 is indicated. The observed α -CH₃/H rate ratio must originate almost entirely from

(24) K. R. Blanchard, Ph.D. Thesis, Princeton University, 1967.

(25) Data from H. C. Brown and M. Borkowski, *J. Amer. Chem. Soc.*, **74**, 1894 (1952), and ref 3b.

(26) Strain calculations on 1 and 2 have been previously carried out by Dr. R. C. Bingham, Ph.D. Thesis, Princeton University, 1970.

electronic considerations. This conclusion strengthens our contention that the value of 10^8 for an α -CH₃/H ratio in limiting (k_c type) solvolyses should serve as a standard against which other such ratios should be interpreted.

Comments on the Conformational Rate Calculation Method. Formerly, the conformational rate calculation method²¹⁻²³ has been applied exclusively to bridgehead systems whose solvolysis rates generally are slower than typical acyclic analogs. A range of reactivities encompassing about 10^{19} has been correlated successfully. In this paper we show that *accelerated* and *non-bridgehead* systems can be treated as well. The total range of reactivities— 10^6 in the present work—now encompasses a total of 25 orders of magnitude!

Direct quantitative comparison of the present results with prior work²¹⁻²³ is difficult. In previous work, the absolute strains tended to be overestimated. This problem was somewhat minimized when differences in strain between the hydrocarbons and cations were considered. In the present work we have employed better parameterization and modified potential functions (see

Table IV. Numerical Values of the Different Parameters Used in the Calculations^a

Bond		Bond Stretching					
		k_r	r_0				
C-C		4.4	1.533				
C-H		4.6	1.096				
+ C-C		7.4	1.480				
+ C-H		7.4	1.084				
Angle Bending ^b		R	R'	R''	θ_0	k_θ	$k_{\theta'}$
		C	C	C	109.5	0.58	0.09
		C	C	H	111.1		
		C	H	H	112.4		
		H	C	C	109.4		
		H	C	H	110.5	0.48	0.09
		H	H	H	111.2		
		H	C	C	106.1	0.36	0.09
		H	C	H	107.7		
+ C-C-C					120.0	2.40	0.0
+ C-C-H					120.0	2.00	0.0
Angle		Torsional ^b			k_ϕ		
CCCC					0.0014		
CCCH					0.0017		
HCCH					0.0021		
		Nonbonded Interactions ^c					
		A	B	C			
C...C		104.0	3.15	4.45			
C...H		30.0	3.415	0.96			
H...H		18.4	3.74	0.19			

^a The following energy functions have been employed in the conformational analysis calculations: bond stretching, $E(r) = \frac{1}{2}k_r(r - r_0)^2$; angle bending, $E(\theta) = \frac{1}{2}k_\theta((\theta - \theta_0)^2 - k_{\theta'}(\theta - \theta_0)^3)$; torsional, $E(\phi) = k_\phi(1 + \cos 3\phi)$; nonbonded interactions, $E(d) = A \exp(-Bd) - C/d^6$. All units are such that energies are in units of 10^{-11} ergs, angles in radians, and distances in ångströms. To convert 10^{-11} erg molecule⁻¹ to kcal mol⁻¹, multiply by 144.0. ^b Angles to be reduced to radians for use. ^c All pairs not in same bond angle interaction, i.e., 1,3 interactions are not included.

Table IV) designed to give accurate absolute strains (at least for hydrocarbons). We have followed the basic approach of Boyd²⁷ in carrying out these strain calculations; however, with some modifications. An anharmonic angle bending function composed of quadratic and cubic terms similar to that employed recently by Allinger^{19c} and use of a pattern-search minimization scheme that has been described previously¹⁷ have been incorporated into our strain program. Other modifications are small changes in the values of a number of parameters such as preferred angles, torsional constants, etc. We have found from our own experience that these strain calculations are not a sensitive function of the parameters employed but that there appears to be room for considerable variation. Cations were treated as described previously,²¹ employing a harmonic angle bending function with angle bending force constants about four times that used in hydrocarbons.

In all our work to date, failure to take the steric effects due to the leaving group into account has been a serious obstacle to a completely general comparison. As has already been mentioned, this is especially important with 2-OPNB-6-OPNB because of the axial nature of the leaving group. This factor is more or less constant with the 2-adamantyl derivatives, 2-OPNB-6-OPNB, but it precludes direct comparison with the bridgehead systems where this factor is absent. We are currently working to extend our computation methods so that leaving groups will explicitly be taken into account. In this manner we hope to make our reaction rate calculation method completely general.

Experimental Section

General. Microanalyses were performed by the Analytical Department of FMC Corporation, Princeton, N. J., Spang Microanalytical Laboratory, Ann Arbor, Mich., and Hoffmann-LaRoche, Inc., Nutley, N. J. Infrared spectra were determined in carbon tetrachloride solutions on either a Perkin-Elmer 237 or 621 spectrophotometer. Nmr spectra were recorded on either a Varian A-60A or JEOLCO JNM-4H-100 spectrometer. Chemical shifts are reported in units of δ (parts per million) relative to internal tetramethylsilane. Gas chromatographic analyses and separations were performed on a Varian-Aerograph 90-P instrument with either a 0.25 in. \times 20 ft 20% Carbowax 20M on 60-80 Chromosorb W or 0.25 in. \times 5 ft 3% SE-30 on 100-120 Varaport 30 columns.

Synthetic. 2-Methyl-2-adamantanol (2-OH) was prepared in 87-95% yield by addition of adamantanone²⁸ to a diethyl ether solution of methylmagnesium iodide at room temperature. Recrystallization from 60-70° petroleum ether gave white, needle-like crystals, mp 216.7-217.4° (lit.²⁹ 214.7-216.5°).

2-Ethyl-2-adamantanol (3-OH) was prepared by the dropwise addition of a solution of adamantanone in diethyl ether to a solution containing a 100 mol % excess of ethyllithium (Foote) in benzene-ether (ca. 3:2) at 0°. Overnight stirring at room temperature, followed by work-up with aqueous ammonium chloride solution, drying (CaCl₂), and solvent removal resulted in a low-melting, yellow residue. Recrystallization twice from pentane at -78° gave an 83% yield of white, crystalline product, mp 66.6-68.8° (lit.²⁹ 69.8°-70.4°).

Ethylmagnesium bromide reacted with adamantanone at 25° to give 40% of 3-OH and 60% of the reduction product, 2-adamantanol. Similar results have been reported by Landa, *et al.*²⁹

2-Neopentyl-2-adamantanol (4-OH) was prepared in 85-90% yield by the addition of adamantanone to a diethyl ether solution of neopentylmagnesium chloride at room temperature. After addi-

(27) S. Chang, D. McNally, S. Shary-Tehrany, M. J. Hickey, and R. H. Boyd, *J. Amer. Chem. Soc.*, **92**, 3109 (1970).

(28) Prepared by the hot sulfuric acid oxidation of adamantane: H. W. Geluk and J. L. M. A. Schlatmann, *Tetrahedron*, **24**, 5361 (1968).

(29) S. Landa, J. Vais, and J. Burkhard, *Collect. Czech. Chem. Commun.*, **32**, 570 (1967).

tion was completed, the reaction mixture was stirred for 12 hr. Work-up and solvent removal yielded a white solid which was recrystallized twice from pentane at -78° : mp $78.0\text{--}78.7^\circ$; ir 3630, 1470, 1360 cm^{-1} ; nmr (CCl_4) δ 1.05 (9 H of *tert*-butyl in neopentyl, s), 3.32 (2 H of methylene in neopentyl, s), 1.20–2.30, most prominent at δ 1.80 (15 H, multiplets).

Anal. Calcd for $\text{C}_{15}\text{H}_{26}\text{O}$: C, 81.02; H, 11.78. Found: C, 81.28; H, 11.86.

2-Isopropyl-2-adamantanol (5-OH) was prepared by the dropwise addition of a pentane solution of adamantanone to a pentane solution containing a 100 mol % excess of isopropyllithium (Alfa Inorganics) under nitrogen at -50° . After addition was complete, the reaction mixture was stirred at 0° for 8 hr. The usual work-up and solvent removal yielded a clear liquid which crystallized on standing. Attempted recrystallization of this material from heptane at -78° was not successful. Sublimation (120° (2 mm)) gave an 80% yield of white, crystalline product, mp $58\text{--}67^\circ$. Further purification of this material by preparative glc gave a product with: mp $72.8\text{--}73.8^\circ$; ir 3610, 1450, 1370, and 1360 cm^{-1} ; nmr (CCl_4) δ 0.82 ($J = 6.6\text{ Hz}$, d, 6 methyl H), 0.97 (1 hydroxy H (?), br s), 1.32–2.45, most prominent at 1.77 (15 remaining H, multiplets).

Anal. Calcd for $\text{C}_{13}\text{H}_{22}\text{O}$: C, 80.11; H, 11.61. Found: C, 79.81; H, 11.84.

2-*tert*-Butyl-2-adamantanol (6-OH) was prepared by the addition of adamantanone to *tert*-butyllithium (Alfa Inorganics) in the same way as in the preparation of 2-isopropyl-2-adamantanol (5-OH). If the reaction mixture was worked up immediately after the addition of adamantanone, the reduction product, 2-adamantanol, was obtained as the major product; however, stirring for 8 hr at 0° before work-up gave 6-OH in high yield.³⁰ Sublimation and recrystallization from acetone at 0° produced an 80% yield of white, crystalline product: mp $59.7\text{--}60.5^\circ$; ir 3620, 1465, and 1360 cm^{-1} ; nmr (CCl_4) δ 1.10 (9 H of *tert*-butyl group, s), 1.27–2.55, most prominent at 1.86 (15 remaining H, multiplets).

Anal. Calcd for $\text{C}_{14}\text{H}_{24}\text{O}$: C, 80.71; H, 11.61. Found: C, 80.67; H, 11.41.

2-Methyl-2-adamantyl *p*-Nitrobenzoate (2-OPNB). 2-Methyl-2-adamantanol (12.1 mmol) and *p*-nitrobenzoyl chloride (12.1 mmol, Aldrich, recrystallized from benzene) were refluxed 1.5 hr in 25 ml of pyridine. Diethyl ether (50 ml) was then added and the solution was extracted four times with 1% sulfuric acid. The organic layer was dried (CaCl_2) and evaporated, and the residue was twice recrystallized from ethanol to give 2.28 g (60% yield) of pale yellow crystals, mp $134.4\text{--}135.0^\circ$ (lit.³¹ $133.1\text{--}133.7^\circ$).

2-Ethyl-2-adamantyl *p*-Nitrobenzoate (3-OPNB). To a solution of 2-ethyl-2-adamantanol (4.0 mmol) in 10 ml of diethyl ether was added a solution of methylolithium (Foote, 5.3 mmol). After stirring for 1 hr at room temperature, a solution of *p*-nitrobenzoyl chloride (4.0 mmol) in 10 ml of diethyl ether was added over a 10-min interval. The yellow solution was stirred for 2 hr at room temperature and then filtered through a sintered glass funnel. The ether was evaporated and the residue was twice recrystallized from diethyl ether–pentane (1:5) at -78° . The pale yellow product was then washed once with ice cold 2% sodium bicarbonate solution and once with water. After drying, 0.335 g (26% yield) of pale yellow product, mp $146.0\text{--}147.7^\circ$ dec (sealed capillary), was obtained: nmr (CDCl_3) δ 0.83 ($J = 7.1\text{ Hz}$, 3 methyl H, t), 1.46–2.68, most prominent at 1.83 (16 H, multiplets), 8.07 (4 aromatic H, s).

Anal. Calcd for $\text{C}_{19}\text{H}_{23}\text{NO}_4$: C, 69.28; H, 7.04; N, 4.25. Found: C, 69.47; H, 6.99; N, 4.37.

2-Neopentyl-2-adamantyl *p*-Nitrobenzoate (4-OPNB) was prepared from 2-neopentyl-2-adamantanol and *p*-nitrobenzoyl chloride by the same procedure used for 3-OPNB. The crude product was twice recrystallized from acetone at 0° to give a white crystalline solid in 70% yield. This product melted at $144.2\text{--}145.6^\circ$, resolidified, ca. 173° , and melted again at $230.5\text{--}232.0^\circ$.³² nmr (CCl_4) δ 1.00 (9 H, s), 2.38 (2 H, s), 1.50–2.80, most prominent at 1.90 (14 H, multiplets), 8.26 (4 aromatic H, s).

Anal. Calcd for $\text{C}_{23}\text{H}_{29}\text{NO}_4$: C, 71.19; H, 7.87; N, 3.77. Found: C, 71.30; H, 7.99; N, 3.57.

(30) In connection with this point, Landa, *et al.*,²⁹ have reported they were unable to prepare 2-isopropyl-2-adamantanol (5-OH) using the lithium alkoxide method under slightly different conditions as employed here, obtaining only 2-adamantanol in their attempts.

(31) P. v. R. Schleyer and R. D. Nicholas, *J. Amer. Chem. Soc.*, **83**, 182 (1961).

(32) This behavior of *p*-nitrobenzoate derivatives has been noted previously; cf. ref 6 and G. J. Abruscato and T. T. Tidwell, *ibid.*, **92**, 4125 (1970).

2-Isopropyl-2-adamantyl *p*-Nitrobenzoate (5-OPNB) was prepared from 2-isopropyl-2-adamantanol and *p*-nitrobenzoyl chloride by the same technique used for 3-OPNB above. The crude product was twice recrystallized from heptane–ether at -78° to give a pale yellow product in 58% yield. This product melted at $158.5\text{--}159.0^\circ$ (sealed capillary), resolidified, and melted (dec) at ca. 220° .³² nmr (CDCl_3) δ 1.05 ($J = 6.8\text{ Hz}$, 6 methyl H, d), 1.50–3.00, most prominent at 1.88 (15 H, multiplets), 8.28 (4 aromatic H, s).

Anal. Calcd for $\text{C}_{20}\text{H}_{25}\text{NO}_4$: C, 69.95; H, 7.34; N, 4.08. Found: C, 70.03; H, 7.69; N, 4.20.

2-*tert*-Butyl-2-adamantyl *p*-Nitrobenzoate (6-OPNB) was prepared in 40% yield from 2-*tert*-butyl-2-adamantanol and *p*-nitrobenzoyl chloride in the same manner as was 3-OPNB. Recrystallization from acetone at 0° gave a pale yellow powder which had no well-defined melting point, but instead steadily decomposed above 150° to long, needle-like crystals: mp ca. $226\text{--}228^\circ$.³² nmr (CDCl_3) 1.26 (9 H of *tert*-butyl group, s), 1.52–3.10, most prominent at 1.80 (14 H, multiplets), 8.27 (4 aromatic H, s).

Anal. Calcd for $\text{C}_{21}\text{H}_{27}\text{NO}_4$: C, 70.55; H, 7.63; N, 3.92. Found: C, 70.56; H, 7.59; N, 4.01.

Solvolysis Product Studies from 2-Methyl-2-adamantyl *p*-Nitrobenzoate (2-OPNB). The following typical procedure and work-up were employed in all the product studies. 2-Methyl-2-adamantyl *p*-nitrobenzoate, 0.322 mmol, was sealed in a heavy-walled glass ampoule together with 25 ml of 80% aqueous acetone and 0.48 mmol of 2,6-lutidine. The solution was heated in a 100° bath for 250 hr, cooled, and shaken with 60 ml of diethyl ether in a separatory funnel. The aqueous layer was saturated with sodium chloride and drawn off. The organic layer was washed once with 10 ml of saturated sodium bicarbonate solution, twice with 10 ml of 1 *N* HCl, and once with 10 ml of saturated sodium bicarbonate solution. It was then dried (CaCl_2), concentrated to ca. 1 ml, and analyzed by glc (Carbowax, 190°). Besides solvent, only two peaks were observed, one of which (82%) had a retention time identical with that of a known sample of methyleneadamantane (6)³¹ and another (18%) whose retention time was the same as that of a known sample of 2-methyl-2-adamantanol (2-OH). Larger scale injections and trapping of the eluents in ice water cooled glass traps yielded the two products, respectively. Ir and nmr spectra confirmed the structural assignments.

Products from 2-Ethyl-2-adamantyl *p*-Nitrobenzoate (3-OPNB). The ester was solvolyzed at 100° for 63.5 hr and worked up as described above. Glc analysis (Carbowax, 210°) showed the presence of three components. The first compound (92%), a colorless liquid, had the following spectral properties: ir 3055, 1665, 1375, and 940 cm^{-1} ; nmr (CCl_4) δ 1.53 ($J = 6.8\text{ Hz}$, 3 methyl H, d), 1.84 (12 H, m), 2.29 (1 H, br s), 2.82 (1 H, br s), 5.01 ($J = 6.8\text{ Hz}$, 1 vinyl H, q). These properties are consistent with the structure of ethylideneadamantane (7).³³ The second compound (1%) had ir absorption at 2910 and 1740 cm^{-1} and was not further characterized. The third compound (7%) had the same retention time and ir and nmr spectra as 2-ethyl-2-adamantanol (3-OH).

Products from 2-Neopentyl-2-adamantyl *p*-Nitrobenzoate (4-OPNB). The ester was solvolyzed at 100° for 75 hr and worked up as described before. Glc analysis (Carbowax, 130°) showed the presence of two components. The first compound (95%) was a colorless liquid with the following spectral properties: ir 3060, 1660, 1370, 845 cm^{-1} ; nmr (CCl_4) δ 1.08 (9 H, s), 1.84 (13 H, m), 3.01 (1 H, br s), 5.01 (1 vinyl H, s).

Anal. Calcd for $\text{C}_{17}\text{H}_{21}$: C, 87.83; H, 12.17. Found: C, 88.01; H, 11.97.

These properties are consistent with the structure of neopentylideneadamantane (8). The second compound (5%) had the same retention time and ir spectra as 2-neopentyl-2-adamantanol (4-OH).

Products from 2-Isopropyl-2-adamantyl *p*-Nitrobenzoate (5-OPNB). The ester was solvolyzed at 100° for 26.5 hr and worked up as before. Glc analysis of the crude product mixture (SE-30, 145°) yielded a compound with a retention time of 5.95 min: mp $42.5\text{--}43.2^\circ$ (sealed capillary); ir 1370 cm^{-1} ; nmr (CCl_4) δ 1.58 (6 methyl H, s), 1.74 (12 H, m), 2.80 (2 H, br s). These properties are consistent with the structure of isopropylideneadamantane (9, lit.³⁴ mp $41.6\text{--}42.2^\circ$).

Anal. Calcd for $\text{C}_{13}\text{H}_{20}$: C, 88.56; H, 11.44. Found: C, 88.74; H, 11.42.

A compound (8%) with a retention time of 11.3 min had the same ir spectrum as 2-isopropyl-2-adamantanol (5-OH); three

(33) J. Vais, J. Burkhard, and S. Landa, *Z. Chem.*, **9**, 268 (1969).

(34) J. Burkhard, J. Vais, and S. Landa, *ibid.*, **9**, 29 (1969).

other fractions with retention times of 7.8 (1%, ir 2910, 1733, 1530, and 1275 cm^{-1}), 12.6 (ca. 2.7%, ir 2910 and 1727 cm^{-1}), and 18.4 min (<0.4%, ir 2920 and 1670 cm^{-1}) were found but not further characterized.

Products from 2-*tert*-Butyl-2-adamantyl *p*-Nitrobenzoate (6-OPNB). The ester was solvolyzed at 50° for 6 hr and worked up as before. Vpc analysis of the crude product mixture (SE-30, 145°) showed the presence of compounds with retention times of 6.5 (1%), 9.3 (83%), and 16.8 min (16%). The first compound was not identified. The third, a white solid, had a retention time, nmr and ir spectrum identical with a known sample of 2-*tert*-butyl-2-adamantan-ol (6-OH). The second compound was a colorless oil: ir 3085, 1633, 1374, and 891 cm^{-1} ; nmr (CCl_4) δ 1.15 (3 methyl H, s), 1.77 (3 methyl allylic H, s), 1.45–2.35 (14 H, multiplets), 4.85 and 4.93 (both slightly split, 1 vinyl H each, singlets). These properties are consistent with the structure of 2-methyl-2-(2'-propenyl)-adamantane (10).³⁵

Anal. Calcd for $\text{C}_{14}\text{H}_{23}$: C, 88.35; H, 11.65. Found: C, 88.38; H, 11.72.

(35) This olefin is also readily formed when alcohol 6-OH either is heated with PBr_3 or is dissolved in pentane and treated briefly with gaseous HBr at 0° in a manner similar to Brown and Rei's chlorination procedure.³⁶

(36) H. C. Brown and M-H. Rei, *J. Org. Chem.*, **31**, 1090 (1966).

Kinetic Studies. Rate measurements were performed in 80% (by volume) aqueous acetone. The acetone was purified by refluxing with potassium permanganate, drying with Drierite, and distillation through a 24-in. Vigreux column prior to use. Titrimetric rates were determined in the usual manner,³⁷ using approximately 0.015 *M* solutions. Conductometric rates were determined using a recording conductivity bridge constructed by Dr. C. J. Lancelot and ca. 10^{-3} *M* solutions of ester in a conductivity cell having bright platinum electrodes and a capacity of ca. 20 ml. Each reaction was run at least in duplicate. Good first-order rate plots were obtained in all cases. Due to its high reactivity and minimal solubility, the rate of solvolysis of 2-*tert*-butyl-2-adamantyl *p*-nitrobenzoate (6-OPNB) was determined conductometrically; a rough titrimetric rate determination on this compound at 50° agreed with the conductometric rate.

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(37) H. C. Brown and Y. Okamoto, *J. Amer. Chem. Soc.*, **77**, 3619 (1955).