hydrolysis since protonation of nitrogen would greatly reduce the basicity of oxygen.

It can be definitely concluded that solvent is participating in the ring-opening step and that this step is subject to general catalysis. It would seem likely that this must also be the case in ring opening of the analogous glucosylamines although the different steric and electronic factors makes such generalization difficult.

Acknowledgment. This work was supported by the National Institutes of Health Research Grant GM 10613-04.

Solvolysis of Bicyclo[2.2.0]hexane-1-methyl *p*-Nitrobenzoate[1a]

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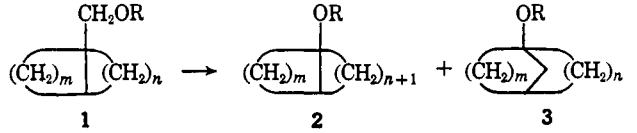
Abstract: Bicyclo[2.2.0]hexane-1-methanol (**10**) was synthesized in a five-step reaction sequence from the Diels–Alder adduct of 5,5-dimethoxytetrachlorocyclopentadiene and ethylene *via* 1,4-dichloro-7,7-dimethoxybicyclo[2.2.1]heptane (**5**), the related 7-ketone **6**, 4-chlorobicyclo[2.2.0]hexane-1-carboxylic acid (**7**), and 4-chlorobicyclo[2.2.0]hexane-1-methanol (**9**). The *p*-nitrobenzoate ester of **10** underwent solvolysis in 60% aqueous acetone at 99.5 and 116.8° to yield 81% of 1-norbornyl *p*-nitrobenzoate (**13**) and 19% 1-norbornanol (**14**). The rate of the reaction is 7×10^6 faster than the extrapolated rate for the corresponding neopentyl derivative. A correlation between rate and strain release is presented as evidence for anchimeric assistance in this type of rearrangement.

Recently the mechanism of the solvolytic reaction of neopentyl-type systems has been analyzed in detail and it has been concluded that in systems where there is little relief of strain by rearrangement the solvolysis proceeds through discrete primary cation ion-pair intermediates and is not anchimerically assisted. In addition, it has been suggested that a mechanism involving participation might be responsible for the enhanced rates observed in some neopentyl-type systems in which substantial strain relief is possible through rearrangement.[2] A series of compounds which appear to encompass both categories are the bicyclo[*m.n.*0]alkane-1-methanols (**1**) since it has been found that as *m* and *n* change from 6,6 to 6,5 to 5,5 the rates of solvolysis at 100° of the *p*-toluenesulfonate esters are 4, 150, and 1000 times, respectively, that of the simple neopentyl derivatives.[3-6] Furthermore, as the rate increases, the type of solvolytic product changes from



1 **2** **3**

2 to **3**. Thus, it continues to be of interest to determine what effects conformation, ring size, and strain have on the course and the rate of neopentyl-type rearrangements.

Bicyclo[2.2.0]hexane-1-methanol (**10**) is of particular interest since it has the highest strain energy of any of the bicyclo[*m.n.*0]alkane-1-methanol systems not containing a cyclopropyl ring; systems containing the latter type of ring system introduce complicating factors due to the unique electronic properties of this ring.[7] The recent preparation of *cis*-4-chlorobicyclo[2.2.0]hexane-1-carboxylic acid[8] has made this interesting ring system available. The acid has been converted to the primary alcohol **10** and the solvolysis of the *p*-nitrobenzoate ester studied.

Synthesis

The Diels–Alder adduct **4** of 5,5-dimethoxytetrachlorocyclopentadiene and ethylene was catalytically hydrogenated to 1,4-dichloro-7,7-dimethoxybicyclo[2.2.1]heptane (**5**). Acid treatment of the ketal **5** gave 1,4-dichlorobicyclo[2.2.1]heptan-7-one (**6**). The chloro ketone **6** reacted readily at 0° with powdered sodium hydroxide in tetrahydrofuran to give *cis*-4-chlorobicyclo[2.2.0]hexane-1-carboxylic acid (**7**). Instability of the Favorskii rearrangement product **7** to the reaction conditions usually used for this type of chloro ketone necessitated the use of milder conditions. This acid **7** was esterified with diazomethane and the ester **8** reduced with lithium aluminum hydride to yield the chlorocarbinol **9**. When large excess of hydride was used in the reduction, loss of the chlorine atom and rearrangement of the nucleus to yield **11** occurred to the extent of 30%. Rearrangement of **9** to **11** probably comes about through ionization (possibly Lewis acid assisted) of the chlorine of **9** alkoxide; a similar rearrangement has been observed in the reaction of **9** with aqueous silver ion.[9] Chlorocarbinol **9** upon reduction with

(1) (a) This work was supported in part by Grant GP-3890, National Science Foundation (to W. G. Dauben), and Grant GM-12731, U. S. Public Health Service, and donors of the Petroleum Research Fund, administered by the American Chemical Society (PRE 2191-A1,4) (to K. V. Scherer). (b) National Institutes of Health Predoctoral Fellow, 1966–1967.

(2) J. E. Nordlander, S. P. Jindal, P. von R. Schleyer, R. C. Fort, Jr., J. J. Harper, and R. D. Nicholas, *J. Amer. Chem. Soc.*, **88**, 4475 (1966).

(3) W. G. Dauben and J. B. Rogan, *ibid.*, 79, 5002 (1957).

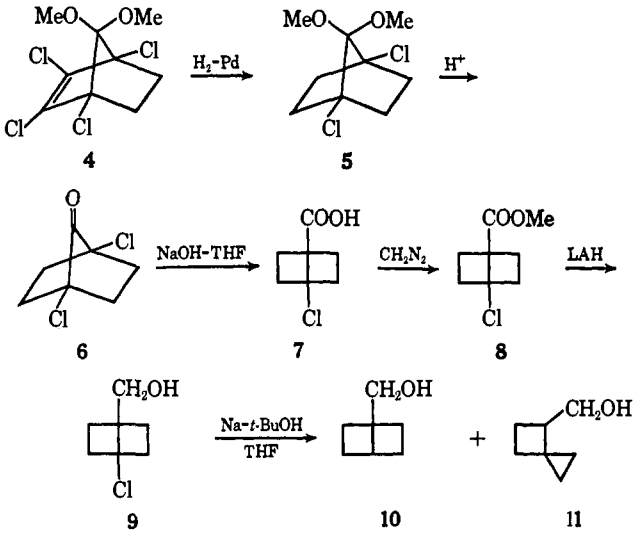
(4) F. T. Bond, Ph.D. Thesis, University of California.

(5) R. A. Flath, Ph.D. Thesis, University of California.

(6) W. G. Dauben, *Bull. Soc. Chim. France*, 1697 (1964).

(7) With rings of three carbon atoms (*m* and/or *n* = 1), the rate of reaction is very rapid and fragmentation is the major reaction pathway. See: (a) K. B. Wiberg, G. M. Lampman, R. P. Ciula, D. S. Connar, P. Schertler, and J. Lavanish, *Tetrahedron*, **21**, 2749 (1965); (b) W. D. Closson and G. T. Kwiatkowski, *ibid.*, **21**, 2779 (1965); (c) W. G. Dauben and J. Wiseman, *J. Amer. Chem. Soc.*, **89**, 3545 (1967).

(8) K. V. Scherer, Jr., *Tetrahedron Letters*, 5685 (1966).



sodium in *t*-butyl alcohol and tetrahydrofuran[10] gave a mixture of the isomeric alcohols **10** and **11** (72:28) which could be separated by preparative vapor phase chromatography. Spectroscopic and chemical properties of these two alcohols, **10** and **11**, are consistent with the assigned structures. Attempts to prepare the *p*-toluenesulfonate ester of **10** under a variety of conditions led only to the isolation of the ester of 1-norbornanol. The *p*-nitrobenzoate ester of **10** was obtained in 86% yield by treatment with *p*-nitrobenzoyl chloride at ice–methanol temperature.

Due to large loss of material in repeated vapor phase chromatographies, the mixture of alcohols, **10** and **11**, was chromatographed only once. Therefore, the samples of bicyclo[2.2.0]hexane-1-methyl *p*-nitrobenzoate (**12**) used for the solvolytic studies contained spiro[2.3]hexane-4-methyl *p*-nitrobenzoate in amounts varying between 2.5 and 7%. Pure spiro[2.3]hexane-4-methyl *p*-nitrobenzoate gave no detectable reaction after remaining under solvolytic conditions for ten half-lives of bicyclo[2.2.0]hexane-1-methyl *p*-nitrobenzoate (**12**) so the presence of this isomeric ester caused no difficulty in either product or rate determination.

Solvolysis

In order to diminish hydrolysis of the esters by the solvolysis medium[11] 2,6-lutidine was added. Under solvolytic conditions in which bicyclo[2.2.0]hexane-1-methyl *p*-nitrobenzoate (**12**) would have reacted to the extent of ten half-lives, a sample of 1-norbornyl *p*-nitrobenzoate (**13**) gave less than 1% of 1-norbornanol (**14**) and a sample of bicyclo[2.2.0]hexane-1-methanol (**10**) was 88% unchanged giving 10.8% of an unidentified material of longer vapor phase chromatography retention time and 1.2% of shorter retention time. A solution of bicyclo[2.2.0]hexane-1-methyl *p*-nitrobenzoate (**12**) in cyclohexane underwent no reaction during 72 hr at 118°. Therefore, the product ratios given reflect the true reaction composition since (a) the starting material was thermally stable at the temperature at which the reaction was conducted, (b) 1-norbornyl *p*-nitrobenzoate (**13**) was stable under solvolysis conditions and, (c) any bicyclo[2.2.0]hexane-1-methanol (**10**) formed would have been sufficiently stable to allow detection.

The ampoule technique was used for the rate determinations. Due to the large amount of internal return, nmr spectroscopy was used to monitor the extent of reaction by recording the spectrum of the isolated esters from each ampoule. The ratio of the integrated areas of aromatic protons (4 H singlet at δ 8.2) to the protons on the carbon atom bearing the ester function (2 H singlet at δ 4.2) was determined. The decrease with time of the signal at δ 4.2 relative to the signal at δ 8.2 was first order. Mathematical correction was made for the loss of aromatic protons as *p*-nitrobenzoic acid due to production of noninternal return product.[12]

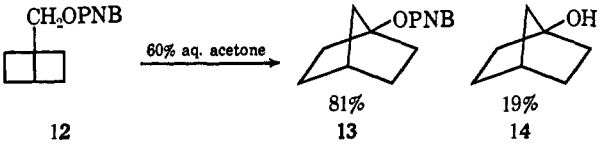
The rate of solvolysis of bicyclo[2.2.0]hexane-1-methyl *p*-nitrobenzoate (**12**) was determined and the results are presented in Table I. The rearrangement proceeded exclusively to the 1-norbornyl system giving 81% internal return to **13** and 19% 1-norbornanol (**14**). These structural assignments were based on comparison of spectral data and melting points with those of authentic compounds.[13]

Table I. First-Order Rate Constants[a] in 60% Aqueous Acetone[b]

Substrate[c]	Temp,[d] °C	$k_1 \times 10^5$,[e] sec^{-1}
Bicyclo[2.2.0]hexane-1-methyl *p*-nitrobenzoate	99.5	0.43
	100.0	0.45 (calcd)
	116.8	1.5

[a] Determined from two runs at each temperature. [b] Solvent contained 2,6-lutidine in 35% molar excess of ester. [c] $0.015 \leq$ [substrate] ≤ 0.020 *M*. [d] $\pm 0.2°$. [e] Largest standard deviation for any rate was $\pm 35\%$.

Due to the inherent limiations of the nmr method for determining rates, these data give the following approximate activation parameters: $\Delta H^{\pm} = 20 \pm 5$ kcal/mol, $\Delta S^{\pm} = -30 \pm 14$ eu.[14,15]

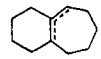
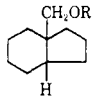
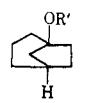
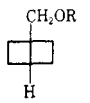
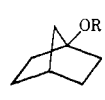
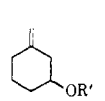
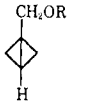
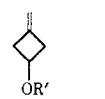
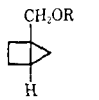
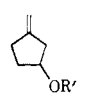


It is of interest to compare the rate and products of solvolysis of bicyclo[2.2.0]hexane-1-methyl *p*-nitrobenzoate (**12**) with those of other *cis*-fused bicyclic neopentyl systems. The rates of these compounds (relative to neopentyl) and the major solvolysis product are given in Table II.

It is also interesting to note that the bicyclo[2.2.0]-hexane-1-methyl system is faster than cyclopropyl-

(9) K. V. Scherer, Jr., and K. Katsumoto, *Tetrahedron Letters*, 3079 (1967).
(10) P. G. Gassman and P. G. Pape, *J. Org. Chem.*, **29**, 160 (1964).
(11) M. S. Silver, *J. Amer. Chem. Soc.*, **83**, 404 (1961).
(12) Let $(a + b + c)/a = 1/$(fraction remaining), where a = mol of **12**; b = mol of **13**; c = mol of **14**; and $(a + b)/a$ = the ratio of the nmr integral at δ 8.2 to the integral at δ 4.2. Since 19.3% of 1-norbornanol is formed in ten half-lives, $c/a = (c/b)(b/a) = (19.3/80.7)(b/a)$. Therefore $(a + b + c)/a = (a + b)/a + (19.3/80.7)[(a + b)/a] - 1\}$.
(13) We wish to thank Professors K. B. Wiberg and D. B. Denney for a sample and spectral data of 1-norbornanol.
(14) See footnote *e* of Table I.
(15) We are indebted to Professor A. Streitwieser for providing copies of LSKIN1 and ACTENG computer programs, both of which were developed by Professor D. F. DeTar, Florida State University.

Table II. Relative Rates and Products of Solvolysis of Bridgehead Carbinyl Tosylates[a] and *p*-Nitrobenzoates[b] at 100°

Compound	Major product (≥75% of product mixture)	Rel k[c]	Ref
$CH_3CH_2CH_2OR$	$CH_3CH=CHCH_3$	1.0	2, 16a
		3.9^d	3
		1.5×10^2	4
		1.0×10^3	5
		3.9×10^4	17
		7×10^6	
		3×10^7	7b
		$>10^8$ [f]	7a
		2×10^{10}	7c

[a] Acetic acid as solvent. [b] Aqueous acetone as solvent. [c] Rates of *p*-nitrobenzoates were compared with neopentyl tosylate by first comparing with cyclopropylcarbinyl tosylate and *p*-nitrobenzoate solvolysis data.[16] [d] Experimental rate data are available for only one temperature (not at 100°). Although an Arrhenius plot for this particular system is not possible without an experimental point at a second temperature, a fair approximation of the rate value at 100° can be obtained by assuming that the slope of an Arrhenius plot for this system would be close to the slopes found for similar systems. The Arrhenius plots were approximately the same for neopentyl systems where rate data were available at two temperatures. [e] 32% was bicyclo[4.3.1]decane-1-acetate. [f] Comparison of rates at 118.6°.

carbinyl *p*-nitrobenzoate in 60% aqueous acetone at 100° by a factor of 150.[16]

It can be seen that as the ring size decreases, the rate of solvolysis and the amount of bridging to yield bicyclo[*m.n.*1]alkane products increases markedly in the bicyclo[*m.n.*0]alkane-1-methyl derivatives. The increasing difficulty of forming a relatively planar carbonium ion as the ring size decreases is not reflected in the solvolysis rates. Rather, the increasing drive to release ring strain and bond-angle deformation results in increasing rate enhancement with participation by the common bond of the fused ring system (the zero bridge bond).

(16) (a) S. Winstein, B. K. Morse, E. Grunwald, K. C. Schreiber, and J. Corse, *J. Amer. Chem. Soc.*, 74, 113 (1952); (b) D. D. Roberts, *J. Org. Chem.*, 29, 294 (1964); (c) see ref 7b; (d) see ref 2.

In all cases the bond involved in the rearrangement is a member of the smaller ring. For the bicyclo[4.4.0]carbinyl system, it might be anticipated that the formation of one seven-membered ring is less difficult than forming two seven-membered rings as would be the case if bridging occurred. The bicyclo[4.3.0]nonane-1-carbinyl system is more balanced between bridging and ring expansion than the others in this series. It gives predominately expansion, relieving the strain of its five-membered ring, but it also bridges substantially (32%), relieving the five-membered-ring's strain but simultaneously forming a seven-membered ring. In all the remaining cases both rings can release their strain simultaneously by bridging. With bicyclo[2.2.0]hexane-1-methyl *p*-nitrobenzoate, the formation of 1-norbornyl derivatives might be favored by any of several factors. Greater strain relief is obtained in going to 1-norbornyl derivatives rather than to 1-bicyclo[3.2.0]heptane derivatives. Also, judging from examination of models, the favored conformer of the starting ester has the leaving group *trans* to and coplanar with the zero bridge bond. To the extent that the transition-state conformation reflects this favored ground-state conformation, the zero bridge bond would be in the best orientation for participation with the developing p lobe during ionization.

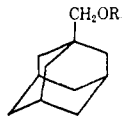
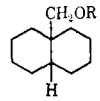
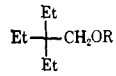
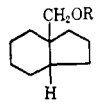
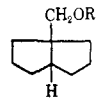
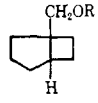
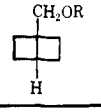
In order to detect internal return with rearrangement in these systems it is necessary that the solvolysis rate of the rearranged and returned tertiary species be slower than that of the neopentyl ester being studied. This condition is met in the case of **12** since there is no detectable solvolysis of 1-norbornyl *p*-nitrobenzoate under conditions used in this study. Internal return was found to the extent of 81% even though 40% of the solvent was water. The bicyclo[3.2.0]heptane-1-methyl system also undergoes internal return with rearrangement.[17] Again, in the bicyclo[3.2.0]heptane-1-methyl system, the rate of solvolysis of the tertiary tosylate is much slower than the neopentyl rearrangement. This is not to say that internal return is not occurring in other members of this series. If the rate of solvolysis of the rearranged, returned ester is greater than the rate of rearrangement, its formation will not be detected by our methods of study.

With these bicyclo[*m.n.*0]alkane-1-methanol systems, one has an opportunity to evaluate the effects of ring strain and conformation on reaction rate and product formation. Inductive effects should be very similar. There is probably not a great difference in solvent accessibility to the reaction site, although accessibility probably increases somewhat as the rings get smaller. If the cyclopropylcarbinyl systems are excluded, the electronic properties are similar and all form tertiary products.

Therefore, it was of interest to see how the rates correlate with potential changes in strain as the reaction progresses from the starting hydrocarbon skeleton to the product hydrocarbon skeleton. Assuming that a portion of this change in hydrocarbon skeletal strain would be experienced at the transition state, one would expect a correlation of this value with rearrangement rate, if there is anchimeric assistance in these solvolyses. The strain values for these systems were estimated, where experimental values were not available, simply as

(17) K. B. Wiberg, private communication.

Table III. Expected Hydrocarbon Strain Release during Solvolysis

Neopentyl compd		Calcd strain release,[a] kcal	Rel rate, 100°
CH_3CCH_2OR (CH_3)			1.0
	(A)	−10.0[b]	1.2[b]
	(B)	−6.3	3.9[c]
	(C)	0.0	5.6[d]
	(D)	6.5	1.5×10^2
	(E)	13.0	1.0×10^3
	(F)	26.4	5.3×10^4 [e]
	(G)	34.3[f]	7×10^6

[a] See ref 18. [b] See ref 2. [c] See footnote *d* of Table II [d] R. L. Heidke and W. H. Saunders, Jr., *J. Amer. Chem. Soc.*, **88**, 5816 (1966). [e] See ref 17. [f] A. F. Bedford, A. E. Beezer, C. T. Mortimer, and H. D. Springall, *J. Chem. Soc.*, 3823 (1963).

the composite of the strains of the component rings.[18] Table III gives the change in hydrocarbon strain energy expected in going from starting material to product during solvolysis for some neopentyl systems of interest.[19]

A least-squares plot of the log of the relative rates of these systems *vs.* potential strain release is linear with a slope of 0.1442/kcal and an intercept of 1.364 at 0.0 kcal, as shown in Figure 1. The correlation coefficient is 0.991. This correlation coupled with the dramatic rate enhancements observed for the more strained compounds of this series strongly suggest anchimeric assistance.

It is interesting to note that if the mechanism were to change from assistance to nonassistance, one would expect the plot to level off when zero strain release was obtained and to remain at this level for those compounds whose solvolysis products are of higher strain energy than the starting neopentyl derivative. This leveling off is not observed. That adamantanecarbinyl (A) and decalylcarbinyl (B) fit on the line is not surprising if ionization and rearrangement are concerted for *all* these neopentyl compounds since the energy gained in forming tertiary carbonium ions would be attained by each compound. Release of strain energy during ionization would complement the energy gained in forming a tertiary carbonium ion, whereas increase in the strain energy during ionization would reduce the net energy gain in forming a tertiary carbonium ion. The consistency of the relationship between rate and strain release, therefore, makes the concept of a single rather than a dual mechanism appear more plausible and suggests that the question of assistance should be reconsidered for those cases where the rate is close to that of neopentyl derivatives.[20]

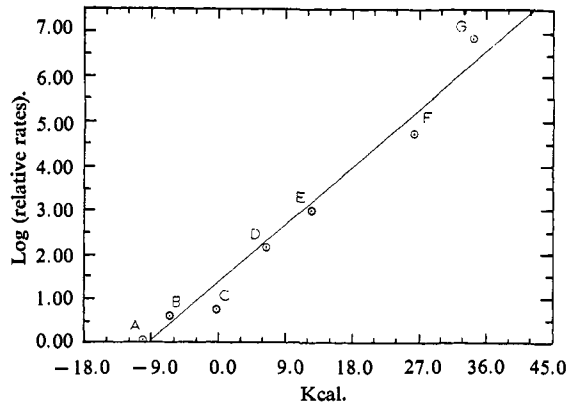


Figure 1. Plot of the log of the experimental relative rate constants plotted against the calculated hydrocarbon–hydrocarbon strain differences. The data used are compiled in Table III. Compound C was not included in the least-squares determination of this line.

It appears that the orientation of the leaving group in relation to the migrating bond is secondary to strain release in determining rate and products. All these compounds fit the correlation line well even though in some cases the maximum strain release is obtained in forming the product which results from migration of the bond in the least favorable conformation for participation (*i.e.*, decalylcarbinyl and hydrindanylcarbinyl systems).

Experimental Section

Melting points were determined with a Laboratory Devices, Mel-Temp apparatus and are uncorrected. The nmr spectra were obtained with TMS as internal standard. Infrared spectra were recorded with Perkin-Elmer 137 and 237 spectrophotometers. Consolidated 103 and Varian M-66 mass spectrometers provided the mass spectra. Vapor phase chromatography was performed on an Aerograph Model A-90-P (thermal conductivity detector) and Hi Fi Model 600-D (hydrogen flame detector). Analyses were performed by the Micro Analytical Laboratory, College of Chemistry, Berkeley, Calif.

The pyridine used was reagent grade material distilled from potassium hydroxide and then from tosyl chloride; it was dried and stored over barium oxide. Dry ether was commercial grade diethyl ether distilled from phosphorus pentoxide, stored over sodium wire, and, in critical cases, distilled from lithium aluminum hydride immediately before use. Tetrahydrofuran, reagent grade from Mallinckrodt, was distilled from lithium aluminum hydride immediately before use. Sodium metal was from Mallinckrodt.

(18) (a) J. D. Roberts and M. C. Caserio, "Basic Principles of Organic Chemistry," W. H. Benjamin, Inc., New York, N. Y., 1965, p 112; (b) E. L. Eliel, N. L. Allinger, S. J. Angyal, and G. A. Morrison, "Conformational Analysis," Interscience Publishers, Inc., New York, N. Y., 1965, p 193.

(19) Neopentyl alcohol derivatives are not included in Figure 1 since they differ from the other compounds in substitution on the carbons which can potentially migrate. A somewhat better acyclic model, the 2,2-diethyl-1-butyl system, is included.

(20) A similar conclusion was reached by Professor W. H. Saunders, Jr., as a result of his recent studies of migratory aptitudes in neopentyl systems. See J. R. Owen and W. H. Saunders, Jr., *J. Amer. Chem. Soc.*, **88**, 5809 (1966), and footnote *d* of Table III.

7,7-Dimethoxy-1,2,3,4-tetrachlorobicyclo[2.2.1]hept-2-ene (4).[21] 5,5-Dimethoxytetrachlorocyclopentadiene[22] (100.8 g) was heated to 185–197° and agitated vigorously for 6 hr while a slow stream of ethylene was introduced through the hollow shaft of a "Vibromischer"; the ethylene flow was adjusted so that only a minimum escaped from the reaction flask *via* a mercury bubbler. Distillation of the crude product at low pressure (10^{-3} mm in the gauge) gave 69.0 g (62%) of **4**, bp 65–68°. The nmr spectrum of **4** consisted of two sharp singlets at δ 3.58 and 3.52, and a centrosymmetric AA'BB' pattern at δ 2.48–1.60.

1,4-Dichloro-7,7-dimethoxybicyclo[2.2.1]heptane (5). A mixture of 32.9 g of **4**, 120 ml of 95% ethanol, and 52 ml of triethylamine was hydrogenated in a Parr shaker over 2.0 g of 5% palladium-on-carbon catalyst. The initial hydrogen pressure was 50 psi, and uptake ceased after 12 hr with consumption of 108% of the calculated amount of hydrogen. The catalyst was separated by filtration and most of the ethanol removed by distillation on the steam bath, and then the crude product was taken up in ether and the ether solution washed successively with water, 3 *N* sulfuric acid, 5% sodium bicarbonate, and saturated sodium chloride solutions. The yellowish waxy residue which remained after evaporation of the ether was recrystallized by dissolving it in a small amount of methanol and chilling the solution to −10°. Two crops of stubby colorless needles were obtained, totaling 23.6 g (93%). One further recrystallization from hexane followed by sublimation under vacuum (50° (10^{-3} mm)) gave an analytical sample, mp 95.0–95.6°. The nmr spectrum of **5** consisted of a sharp singlet at δ 3.60 and a centrosymmetric multiplet at δ 2.4–1.6.

Anal. Calcd for $C_9H_{14}Cl_2O_2$: C, 48.02; H, 6.27; Cl, 31.50. Found: C, 47.85; H, 6.24; Cl, 31.52.

4-Chlorobicyclo[2.2.0]hexane-1-carboxylic Acid (7).[8] Concentrated sulfuric acid (50 ml) was added to a solution of 20.05 g of ketal **5** in 200 ml of dichloromethane, and the mixture was stirred magnetically for 5.25 hr. The dichloromethane solution of crude 1,4-dichlorobicyclo[2.2.1]heptan-7-one (**6**) was carefully separated from the dark sulfuric acid layer, filtered through a plug of cotton to entrap the last globules of acid, and without further washing distilled to dryness on the steam bath. Ketone **6**, which may crystallize exothermically as the last traces of solvent are removed, is obtained in quantitative yield as a mass of fine colorless-to-tan needles, $\nu_{C=O}^{CS_2}$ 1815 cm^{-1}, and is used directly in the next step. (The ketone readily forms a hydrate on exposure to moist air, but the consequences of using hydrated material for the rearrangement step have not been explored.) The crude **6** from 20.05 g of **5** was dissolved in 200 ml of tetrahydrofuran which had been freshly distilled from solid potassium hydroxide (*caution*)[23] and the solution was cooled in an ice bath and stirred magnetically. To the cold solution was then added 16.5 g of finely powdered sodium hydroxide in one portion, and the flask was closed with a Drierite tube and stirred for 5 hr. The initially fluid slurry gradually thickened and finally gelled near the end of the reaction, stopping the stirrer. The mixture was worked up by adding 40 ml of concentrated hydrochloric acid in small portions, still keeping the mixture cold, followed by 50 ml of water, and then most of the tetrahydrofuran was removed under vacuum at room temperature with a rotary evaporator. The crude product was taken up into 200 ml of ether, the ether solution was washed with water, and the acid was extracted from it into ice-cold 5% aqueous sodium bicarbonate solution, which was immediately reacidified with dilute acid. The precipitated acid was reextracted with one 150-ml portion of ether, and the ethereal extract was washed with a saturated sodium chloride solution, evaporated to dryness, and pumped briefly at 10^{-3} mm. The yield of crude acid, mp 110–137°, was 13.23 g (92.6%); its infrared spectrum was substantially the same as that of the analytical sample. A sample was prepared for analysis by recrystallization from aqueous ethanol, then carbon tetrachloride, and sublimation at 60–65° (10^{-3} mm); mp 143.0–143.9°. The best solvent for recrystallization is ether, with cooling to −10° for good recovery.

Anal. Calcd for $C_7H_9ClO_2$ (160.60): C, 52.35; H, 5.65; Cl, 22.07. Found: C, 52.21; H, 5.61; Cl, 22.28; equiv wt, 160.

Methyl Ester of 4-Chlorobicyclo[2.2.0]hexane-1-carboxylic Acid (8). An ethereal solution of diazomethane was added dropwise to 5.4 g of 4-chlorobicyclo[2.2.0]hexane-1-carboxylic acid (7) in 50 ml of diethyl ether until the yellow color remained. The solution stirred at room temperature for 3.5 hr and the ether was then distilled through a 12-in. Vigreux column at atmospheric pressure giving 8.2 g of crude ester. The ester could be vpc collected from an SE-30 column, mp 20–25°; $\nu_{max}^{CCl_4}$ 2998, 2992, 1735, 1430, 1250, 1240, 1200, 1170, and 1130 cm^{-1}; nmr (δ, CCl_4) 3.5 (3 H, singlet, methyl), 3.1–2.4 (4 H, complex), and 2.3–1.7 (4 H, complex).

Anal. Calcd for $C_8H_{11}O_2Cl$: C, 55.00; H, 6.35; Cl, 20.31. Found: C, 55.14; H, 6.39; Cl, 20.58.

4-Chlorobicyclo[2.2.0]hexane-1-methanol (9). A stirred solution of 4.75 g (0.027 mol) of the methyl ester of 4-chlorobicyclo[2.2.0]-hexane-1-carboxylic acid (**8**) in 300 ml of dry diethyl ether was cooled in an ice bath and 0.93 g (0.027 mol, 4 equiv) of lithium aluminum hydride was added. The mixture was stirred at 0° for 4 hr. Methanol and then saturated ammonium chloride solution were added until salts precipitated. The ether layer was decanted, and the salts were washed with ether. The combined ethereal solution was washed with water, saturated sodium bicarbonate solution, and water and dried over anhydrous sodium sulfate. The ether solution was filtered and the ether removed by rotary evaporation giving 2.7 g of 4-chlorobicyclo[2.2.0]hexane-1-methanol (68%); mp 61–67°; $\nu_{max}^{CCl_4}$ 3450, 2980, 2910, 2840, 1445, 1425, 1370, 1250, 1205, 1170, 1150, 1030, and 880 cm^{-1}; nmr (δ, CCl_4): 3.5 (2 H, singlet), 3.1 (1 H, broad singlet, hydroxyl), 2.8–1.5 (8 H, complex).

Anal. Calcd for $C_7H_{11}OCl$: C, 57.33; H, 7.56; Cl, 24.19. Found: C, 57.16; H, 7.72; Cl, 24.08.

Reduction of 4-Chlorobicyclo[2.2.0]hexane-1-methanol (9). Finely divided sodium (2.36 g) was added to a stirred solution of 1.12 g of 4-chlorobicyclo[2.2.0]hexane-1-methanol (**9**) in 31.3 ml of tetrahydrofuran and 3.11 g (3.95 ml) of *t*-butyl alcohol. The mixture was stirred under nitrogen at reflux for 23 hr. The mixture was filtered through a wire screen into a separatory funnel containing ice and water. This aqueous phase was extracted with three portions of diethyl ether. The combined extracts were washed with 1% hydrochloric acid, saturated sodium bicarbonate, and water and dried over anhydrous sodium sulfate. The solution was then filtered and the ether distilled at atmospheric pressure. The residue was distilled at 60° (0.1 mm) into a receiver cooled to −78°. The combined yield of alcohols was 0.53 g (62%). Analysis by nmr showed 28% of the alcohols obtained was spiro[2.3]hexane-4-methanol (**11**); the remainder was the expected bicyclo[2.2.0]-hexane-1-methanol (**10**). The two isomers were separated by preparative vapor phase chromatography.

Spectral results for bicyclo[2.2.0]hexane-1-methanol (**10**) were as follows: $\nu_{max}^{CCl_4}$ 3460, 2980, 2950, 2860, and 1030 cm^{-1}; nmr (δ, CCl_4): 3.4 (2 H, singlet), 3.3 (1 H, broad singlet, hydroxyl), 2.7–1.7 (9 H, complex), mass spectrum (*m/e*): base peak, 82; molecular ion, 112.

Anal. Calcd for $C_7H_{12}O$: C, 74.95; H, 10.78. Found: C, 74.81; H, 10.55.

Spectral results for spiro[2.3]hexane-4-methanol (**11**) were as follows: $\nu_{max}^{CCl_4}$ 3400, 3080, 2930, 2850, and 1005 cm^{-1}; nmr (δ, CCl_4): 3.5 (2 H, doublet, J = 7 cps), 2.8 (1 H, broad singlet, hydroxyl), 2.6–1.4 (5 H, complex), 0.47–0.08 (4 H, complex); mass spectrum (*m/e*): base peak, 79; molecular ion, 112.

Anal. Calcd for $C_7H_{12}O$: C, 74.95; H, 10.78. Found: C, 74.78; H, 10.57.

Bicyclo[2.2.0]hexane-1-methyl *p*-Nitrobenzoate (12). A 207.7-mg (1.86 mmol) portion of bicyclo[2.2.0]hexane-1-methanol (**10**) (97.5% pure; the remaining material was isomeric) in 33.3 ml of dry pentane and 1.67 ml of carbon tetrachloride was cooled with stirring in an ice–methanol bath and 400 mg (10% excess) of *p*-nitrobenzoyl chloride was added. The mixture was stirred 2.5 hr. The solution was then poured into 75 ml of water and extracted with one 150-ml portion of pentane and five 25-ml portions of pentane. The combined pentane extracts were washed with two 25-ml portions of iced 1% hydrochloric acid, three 25-ml portions of saturated sodium bicarbonate solution, and three 25-ml portions of water and dried over anhydrous sodium sulfate. The pentane was then removed by rotary evaporation. Pyridine was still present so the oily residue was dissolved in pentane and the washings and drying were repeated. Rotary evaporation for 30 min at room temperature (5 mm) gave 424.3 mg (87%) of *p*-nitrobenzoate as white crystals. Sublimation at 10 μ from an 80° oil bath gave 416.3 mg (86%) of ester, mp 84–88°; $\nu_{max}^{CCl_4}$ 2940, 2900, 2810, 1720, 1530, 1340, 1270, 1010, 882, and 720 cm^{-1}; nmr (δ, CCl_4): 8.2 (4 H, singlet, aromatic), 4.2 (2 H, singlet), 2.9–1.6 (9 H, complex); mass spectrum *m/e*: base peak, 150; molecular ion, 261.

(21) (a) P. E. Hoch, *J. Org. Chem.*, **26**, 2066 (1961); (b) P. G. Gassman and P. G. Pape, *ibid.*, **29**, 160 (1964).

(22) E. T. McBee, D. L. Crain, L. R. Belohlav, and H. P. Braendlin, Jr., *J. Amer. Chem. Soc.*, **84**, 3557 (1962).

(23) *Org. Syn.*, **46**, 105 (1966).

Anal. Calcd for $C_{14}H_{15}O_4N$: C, 64.36; H, 5.79; N, 5.36. Found: C, 64.18; H, 5.76; N, 5.52.

Attempted Preparation of Bicyclo[2.2.0]hexane-1-methyl Tosylate. A 76.4-mg portion of tosyl chloride was added to a solution of 29.4 mg of alcohol **10** in 1.5 ml of pyridine at 0°. The mixture was stirred at room temperature for 17 hr, and an additional 50 mg of tosyl chloride was added. After 25 hr the solution was poured into iced 10% hydrochloric acid and extracted with six portions of pentane. The combined pentane extracts were washed with a saturated solution of sodium bicarbonate and dried over anhydrous sodium sulfate, keeping the extracts cold. The ether was removed under reduced pressure to yield 54.8 mg (93%) of a tosylate. Both the nmr and the infrared spectra were identical with those of 1-norbornyl tosylate made by an analogous procedure from an authentic sample of 1-norbornanol. The melting point of 1-norbornyl tosylate was 25–26° (lit.[24] 29.2–29.8°).

Two other methods[25] were tried but the only tosylate formed was rearranged.

1-Norbornyl *p*-Nitrobenzoate (13). A 28.9-mg portion of 1-norbornanol (**14**) was dissolved in 5.5 ml of pyridine and 240 μl of carbon tetrachloride. To this solution was added 62 mg of *p*-nitrobenzoyl chloride. The mixture was stirred 4 hr at room temperature, poured into water, and extracted with four portions of pentane. The pentane was washed with two portions of 1% hydrochloric acid (iced), a saturated sodium bicarbonate solution, and water and dried over a mixture of anhydrous magnesium and sodium sulfates. The solution was then filtered and rotary evaporated. The residue was sublimed at 55° (20 μ) to give 62 mg (90%) of ester, mp 101–103°; $\nu_{max}^{CCl_4}$ 2980, 2880, 1740, 1530, 1280, 1255, 1130, and 865 cm^{-1}; nmr (δ, CCl_4): 8.1 (4 H, singlet, aromatic), 2.3–1.2 (11 H, complex); mass spectrum (*m/e*): base peak, 150; molecular ion, 261.

Anal. Calcd for $C_{14}H_{15}N$: C, 64.36; H, 5.79; N, 5.36. Found: C, 64.40; H, 5.91; N, 5.52.

General Methods and Materials for Rearrangement Studies. Bicyclo[2.2.0]hexane-1-methanol (**10**) was vpc collected, and the product contained no more than 6% of isomeric alcohols. The solvent was prepared as follows. Reagent grade acetone was refluxed over potassium hydroxide and Drierite according to the methods of Hammond and Kochi[26] and distilled through a 5-ft Vigreux column, taking the center cut. Water was distilled before use. The ratio of acetone to water was 60:40 by volume. Reagent grade 2,6-lutidine was distilled through an 18-in. spinning band, taking the center cut; bp 142.8–143.0°. The ampoule technique was used. After each Pyrex tube was filled with measured amounts of solvent, ester and, for most runs, lutidine, the tubes were evacuated, first under aspirator pressure and then 2–4 mm as the tube was cooled in a Dry Ice–acetone bath. The tubes were sealed at this reduced pressure. After measured intervals at the solvolysis temperature, each tube was withdrawn, cooled, opened, poured into a saturated solution of sodium bicarbonate, and extracted with three portions of diethyl ether. The combined ether extracts were washed with saturated sodium bicarbonate and water and dried over a mixture of anhydrous magnesium and sodium sulfates. The ether solutions were then filtered and rotary evaporated. The solid residues were taken up in carbon tetrachloride and their nmr spectra recorded. Three separate spectra were recorded for the contents of each ampoule and ten integrations run of each spectrum. The ratio of the average integrated areas of aromatic protons (δ 8.2) to the methylene protons at δ 4.2 were recorded to monitor the extent of rearrangement.

Determination of Rearrangement Products. Two 25-mg samples of bicyclo[2.2.0]hexane-1-methyl *p*-nitrobenzoate (**12**) were placed in two thick-walled Pyrex tubes each containing 5 ml (0.02 *M* in ester) of 60% aqueous acetone. The tubes were cooled in an ice–water bath and then a Dry Ice–acetone bath as they were evacuated to 10 μ. They were sealed and placed in a 117° bath for 259 hr. The tubes were then cooled, opened, poured into water, and extracted with diethyl ether. The ether solution was washed with a saturated sodium bicarbonate solution and water, and then dried over anhydrous sodium sulfate. The solution was filtered and the ether removed at reduced pressure. The predominate solvolysis product appeared by nmr to be rearranged *p*-nitrobenzoate. Therefore the residue was taken up into 50 ml of diethyl ether, stirred, and treated with 20 equiv of lithium aluminum hydride for 2 hr at room temperature. Methanol and then saturated ammonium chloride solution were added until salts had precipitated and a clear, yellow solution was left. The solution was decanted, dried, filtered, and rotary evaporated. The residue gave a single peak on a 5-ft 10% Carbowax (10% KOH) column; mp 150–152° (sealed tube) (lit.[27] 151–154°). The ir and nmr matched those of 1-norbornanol (**11**); $\nu_{max}^{CCl_4}$ 3330, 2950, 2880, 1450, 1320, 1255, 1220, 1170, 1130, 1090, and 925 cm^{-1}; nmr (δ, CCl_4): 4.0 (1 H, broad singlet, hydroxyl), 2.0 (1 H, complex), 1.6, 1.5, and 1.4 (10 H, equal area broad singlets); mass spectrum (*m/e*): base peak, 83; molecular ion, 112.

To ascertain the amount of internal return, a 10.5-mg portion of bicyclo[2.2.0]hexane-1-methyl *p*-nitrobenzoate (**12**) was sealed under vacuum with 6 ml of 60% aqueous acetone containing 5.9 mg (35% in excess of ester) of 2,6-lutidine. After ten half-lives at 117°, the tube was cooled to room temperature and opened, and 3.3 mg of cyclohexanol was added. The contents of the tube were then emptied into a separatory funnel containing a saturated solution of sodium bicarbonate, and the remaining contents of the tube were washed into the separatory funnel with diethyl ether. The organic material was extracted with diethyl ether and the ethereal solution was dried over anhydrous magnesium sulfate. A comparison by vpc of the areas of 1-norbornanol (**11**) and cyclohexanol showed 19.3% 1-norbornanol was formed. Therefore, the remaining 80.7% was 1-norbornyl *p*-nitrobenzoate (**13**). This was confirmed by removing, under vacuum, 1-norbornanol from the solvolysis mixture and comparing the ir and nmr spectra of the remaining 1-norbornyl *p*-nitrobenzoate with those of 1-norbornyl *p*-nitrobenzoate made from 1-norbornanol. To determine if the ratios of the vpc areas reflected the true weight ratios, the vpc ratio of a weighed mixture of 1-norbornanol and cyclohexanol was checked. A similar experiment at 99.5° gave 19.1% 1-norbornanol and 80.9% 1-norbornyl *p*-nitrobenzoate.

Kinetics of Rearrangement. For each run, six tubes were prepared containing approximately 30 mg of ester and 21 μl (18 mg) of lutidine (45% molar excess over ester) in 6 ml of 60% aqueous acetone (0.02 *M* in ester). Two runs were made at 116.8° and two at 99.5°.

Blank Experiments and Stability Checks. A 19.0-mg portion of alcohols, 91% bicyclo[2.2.0]hexane-1-methanol (**10**) and 9% spiro[2.3]hexane-4-methanol (**11**), was converted to *p*-nitrobenzoate as usual and then reduced with 20 equiv of lithium aluminum hydride at room temperature. Analysis by vpc showed no change in the ratio of the two alcohols.

A sample of bicyclo[2.2.0]hexane-1-methyl *p*-nitrobenzoate (**12**) was dissolved in cyclohexane and sealed in a Pyrex tube. The tube was maintained at 118° for 72 hr. The product was identical with starting material by nmr.

A 5-mg portion of freshly sublimed spiro[2.3]hexane-4-methyl *p*-nitrobenzoate was dissolved in 2 ml of 60% aqueous acetone and sealed under vacuum. The tube was maintained at 117° for 242 hr and worked up as usual. The ir of the product was identical with that of starting ester, and no alcohol was detectable by vpc, showing that this ester was not reactive under these conditions.

Table IV. Determinations of Stability to Solvolytic Conditions

Tube	Contents,[a] mg	Products[b]
1	9.8, 1-norbornyl *p*-NB (**13**)	4% 1-norbornanol (**14**)
2	9.3, 1-norbornyl *p*-NB 1.7, *p*-nitrobenzoic acid (0.25 equiv) 5.5, lutidine (1.25 equiv)	<1% 1-Norbornanol
3	7.8, *p*-nitrobenzoic acid (1 equiv) 5.1, bicyclo[2.2.0]hexane-1-methanol (**10**) 9.6, lutidine (2 equiv)	88% unchanged (90% of the 12% which changed went to longer retention time material; 10%, to shorter retention time material)

[a] In 6 ml of 60% aqueous acetone. [b] Besides ester.

(24) K. B. Wiberg and B. R. Lowry, *J. Amer. Chem. Soc.* **85**, 3188 (1963).

(25) Procedure outlined here was that of R. S. Tipson, *J. Org. Chem.*, **9**, 239 (1944). The other procedures were: J. K. Kochi and G. S. Hammond, *J. Amer. Chem. Soc.*, **76**, 3443 (1953), and K. B. Wiberg, G. M. Lampman, R. P. Ciula, D. S. Connor, P. Schertler, and J. Lavanish, *Tetrahedron*, **21**, 2749 (1965).

(26) G. S. Hammond and J. K. Kochi, *J. Amer. Chem. Soc.*, **75**, 3445 (1953).

(27) D. B. Denney and R. R. DiLeone, *ibid.*, **84**, 4737 (1962).

In order to determine stability to reaction conditions, the experiments compiled in Table IV were performed. In each case the compounds in question were dissolved in sufficient solvent to reproduce solvolysis concentrations. Each tube was maintained at 117° for ten half-lives (approximately 150 hr). The amount of alcohol produced in each case was obtained by adding a weighed amount of cyclohexanol and determining from vpc traces the relative area of a given alcohol to that of the cyclohexanol standard.

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The Acid-Catalyzed Hydration of Phenylacetylene. Evidence for the Vinyl Cation Intermediate[1,2]

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Abstract: The acid-catalyzed hydration of phenylacetylene parallels the acidity function, a plot of log k_{obsd} against $-H_0$ having a slope of 1.24. The reaction involves a rate-determining proton transfer as shown by the solvent isotope effect, k_{H_2O}/k_{D_2O} being 2.5. The rate of hydration of substituted phenylacetylenes is extremely sensitive to the nature of substituents in the ring, and correlation with σ^+ constants gives a ρ value of -3.84. Examination of the rate of hydration of *p*-methoxyphenylacetylene in aqueous buffers reveals that the reaction is subject to general acid catalysis. Evidence to demonstrate that the first intermediate in the hydration reaction is a vinyl cation is presented. A small amount of exchange of the acetylenic hydrogen of phenylacetylene in strongly acidic media is observed.

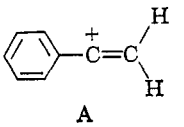
In a continuation of our studies of the mechanisms of the reactions of unsaturated systems with acid, we have examined the acid-catalyzed hydration of phenylacetylene. These studies represent a natural supplement of previously reported studies on phenylpropiolic acid[4] and phenylbenzoylacetylene.[5]

As these studies were in progress Bott, *et al.*,[6] reported the relative rates of hydration of several substituted phenylacetylenes in acetic acid–water–sulfuric acid mixtures and noted the strong sensitivity of the reaction to the electron demands of the substituent. Bott, *et al.*,[6] concluded that the reaction rates as measured were best fit by the Yukawa–Tsuno equation.[7]

We have examined this reaction under a variety of different circumstances in order to gain more mechanistic insight into the nature of the intermediates involved. The hydration of phenylacetylene (**1**), *p*-methoxyphenylacetylene (**2**), *p*-methylphenylacetylene (**3**), and *p*-chlorophenylacetylene (**4**) has been studied in aqueous sulfuric acid. The reaction is smooth and quantitative when the concentration of organic substrate is kept low. Bott, *et al.*,[6] have commented upon the difficulty of reproducing on a preparative scale the quantitative conversion of phenylacetylene to acetophenone as shown by spectral changes at 10^{-5} *M* levels. The suggestion that subsequent bimolecular aldol condensation destroys some acetophenone is in complete accord with our observations as well.

The hydration reaction shows strong acid catalysis, plots of the logarithm of the observed rate constants *vs.* H_0 being linear. Such a plot for **1** has a slope of -1.24 at 25°. Measured rate data for phenylacetylene and three substituted phenylacetylenes is given in Table I; Tables II and III contain derived information.

The activation energies and entropies of activation accord with those to be expected for a rate-limiting proton transfer. As we reported briefly earlier,[2] the evidence including the solvent isotope effect[8] supports the rate-limiting formation of a vinyl cation intermediate of structure **A**.



A

General Acid Catalysis. A rate-determining proton transfer to phenylacetylene (eq 1) implies general acid

$$C_6H_5C{\equiv}CH + H^+ \xrightarrow{\text{slow}} A \qquad (1)$$

catalysis. To examine whether general acid catalysis is, in fact, operative, it is only necessary to examine the behavior of a sufficiently reactive substituted phenylacetylene; *p*-methoxyphenylacetylene (**2**) is satisfactory.

At 45° the rate of hydration of **2** may be followed in formic acid–formate buffers; the data are given in Table IV.

(1) Supported in part by a grant from the Petroleum Research Fund administered by the American Chemical Society. Grateful acknowledgment is made to the donors of these funds.

(2) A portion of this material has been published in preliminary form: D. S. Noyce, M. A. Matesich, M. D. Schiavelli, and P. E. Peterson, *J. Amer. Chem. Soc.*, 87, 2295 (1965).

(3) National Science Foundation Predoctoral Fellow, 1964–1966; National Institutes of Health Predoctoral Fellow (GM-33,805-01), 1966–1967.

(4) D. S. Noyce, M. A. Matesich, and P. E. Peterson, *J. Amer. Chem. Soc.*, 89, 6225 (1967).

(5) D. S. Noyce and K. E. DeBruin, *ibid.*, 90, 372 (1968).

(6) R. W. Bott, C. Eaborn, and D. R. M. Walton, *J. Chem. Soc.*, 384 (1965).

(7) Y. Yukawa and Y. Tsuno, *Bull. Chem. Soc. Jap.*, 32, 965, 971 (1959).

(8) The solvent isotope effect, k_{H_2O}/k_{D_2O}, for phenylacetylene is 2.5 at an H_0 of -2.0. It will be discussed in detail in a forthcoming paper.