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SECONDARY α-DEUTERIUM KINETIC ISOTOPE EFFECTS IN SOLVOLYSES OF 2-CYCLOPENTYLETHYL, 2-(Δ²-CYCLOPENTENYL)ETHYL, AND 2-(Δ³-CYCLOPENTENYL)ETHYL *p*-NITROBENZENESULPHONATES[1]

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Abstract—The kinetics of solvolysis of 2-cyclopentylethyl, 2-(Δ²-cyclopentenyl)ethyl and 2-(Δ³-cyclopentenyl)ethyl *p*-nitrobenzenesulphonates (I, II and III, respectively) and the corresponding 1,1-dideuterated analogs, I-d_2, II-d_2 and III-d_2, were studied in 25% water–75% dioxane and in glacial acetic acid at a number of temperatures. The very small k_H/k_D values observed for I and I-d_2 suggest considerable S_N2 character for the solvolysis of this system. Small but appreciable isotope effects were noted for II and II-d_2. Solvolyses of III and III-d_2 showed the highest isotope effects, k_H/k_D for acetolysis being about 1·14. This value is much less than an expected rate retardation of about 15% per α-deuterium atom for acetolysis with a limiting or S_N1 mechanism. The results are interpreted as in agreement with Streitwieser's postulation that neighboring group participation in the rate-determining step will lower the magnitude of the α-deuterium kinetic isotope effect. Consideration of the activation parameters suggest the probability that for the systems studied, differences in enthalpies rather than entropies of activation contribute more to the rate retardation after deuterium substitution at the α-carbon.

SOLVOLYSES of 2-(Δ³-cyclopentenyl)ethyl *p*-toluenesulphonate or *p*-nitrobenzenesulphonate give high yields of *exo*-norbornyl products via 1,5-participation of the double bond.[3–5] In view of the current interest in the norbornyl system;[6–11] and since it has been suggested by Streitwieser[12–13] that participation of a neighboring group in the rate-determining step of a carbonium ion reaction would lower the magnitude of the secondary α-deuterium kinetic isotope effect, a study was undertaken on the kinetic

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[3] R. G. Lawton, *J. Amer. Chem. Soc.* **83**, 2399 (1961).
[4] P. D. Bartlett and S. Bank, *J. Amer. Chem. Soc.* **83**, 2591 (1961).
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[12] A. Streitwieser, Jr., R. H. Jagow, R. C. Fahey and S. Suzuki, *J. Amer. Chem. Soc.* **80**, 2326 (1958).
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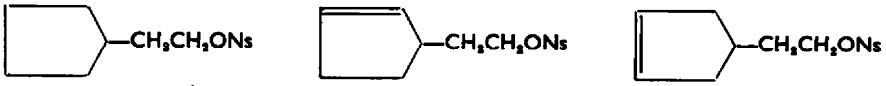
isotope effects in solvolyses of 2-cyclopentylethyl, 2-(Δ^2-cyclopentenyl)ethyl and 2-(Δ^3-cyclopentenyl)ethyl *p*-nitrobenzenesulphonates (I, II and III, respectively), and their 1,1-dideuterated analogs, I-d_2, II-d_2 and III-d_2.



I II III

ONs = *p*-nitrobenzenesulphonate, *p*-$NO_2C_6H_4SO_3$

RESULTS AND DISCUSSION

Cyclopentylacetic acid and Δ^2-cyclopentenylmalonic acid were obtained commercially. Decarboxylation of the latter gave Δ^2-cyclopentenylacetic acid. Δ^3-Cyclopentenylacetic acid was derived from the malonic ester synthesis starting with 4-bromocyclopentene[14] and diethyl malonate. Reduction of these substituted acetic acids with either lithium aluminum hydride or lithium aluminum deuteride afforded the appropriate alcohols from which the desired *p*-nitrobenzenesulphonates, I, II, III, I-d_2, II-d_2 and III-d_2, were prepared. Analyses[15] showed that I-d_2, II-d_2 and III-d_2 contained, respectively, 1·93, 1·92 and 1·94 D atoms per molecule.

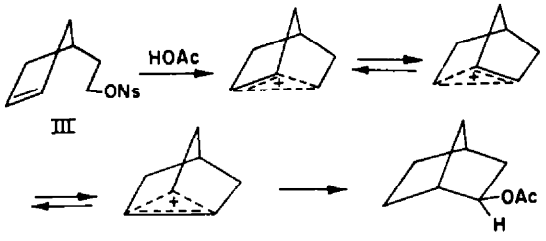
The kinetics of solvolysis of the *p*-nitrobenzenesulphonates in either 25% water–75% dioxane or glacial acetic acid were determined at a number of temperatures. The first order specific rate constants were obtained in the usual way from plots of the appropriate data using the least squares method with the aid of a digital computer. The k values together with the corresponding 95% confidence limits (standard deviations × 1·96), and the isotope effects as measured by k_H/k_D, are summarized in Table 1. The relative rates for the protio compounds, and the enthalpies and entropies of activation derived from least squares plots of log k against reciprocals of absolute temperature, were calculated for 60·65° and tabulated in Table 2.

The literature and various interpretations of secondary deuterium isotope effects have recently been critically reviewed by Halevi.[16] While its origin is still a matter of some controversy, a working hypothesis, suggested by Streitwieser,[12,13] has attributed the α-deuterium kinetic isotope effect largely to "the decrease in a bending force constant from a starting tetrahedral C—H bending vibration to the generally lower out-of-plane bending motion in the transition state leading to the carbonium ion."[13] This hypothesis, considered together with the possible influence from the electron releasing inductive effect of deuterium,[16,17] led to the prediction that, for a direct displacement reaction, the α-kinetic isotope effect would virtually vanish or become inverse, and that a neighboring group participating in the rate-determining step would result in a lowering of this isotope effect from the generally observed rate retardation of about 15% per α-deuterium atom for carbonium ion reactions such as acetolysis.[12,13]

Considering the results in Table 1, the very low isotope effects observed for I and I-d_2 suggest that solvolysis of this system in aqueous dioxane or in acetic acid likely involves a mechanism with considerable S_N2 character. On the other hand, in the

[14] P. D. Bartlett and M. R. Rice, *J. Org. Chem.* **28**, 3351 (1963).
[15] By Josef Nemeth, Urbana, Ill.
[16] E. A. Halevi, *Progress in Physical Organic Chemistry* (Edited by S. G. Cohen, A. Streitwieser, Jr. and R. W. Taft) Vol. 1, pp. 101–221. Interscience, New York, N.Y. (1963).
[17] A. Streitwieser, Jr. and H. S. Klein, *J. Amer. Chem. Soc.* **85**, 2759 (1963).

solvolysis of III, the very high yields of norbornyl products[3–5] arising from participation of the Δ^3-double bond indicate a limiting or S_N1 mechanism. The observed isotope effect in the acetolysis of III and III-d_2 of about 1·14 for two α-deuterium atoms, or about 7% rate retardation per α-deuterium, is much less than the expected value of about 15% rate retardation per α-D for a limiting carbonium ion reaction. The decreased magnitude of this observed isotope effect, in accordance with Streitwieser's suggestion, may be attributable to the participation in the rate-determining step of the Δ^3-double bond which led to ring closure, and possibly also in part to the inductive effect of two α-deuterium atoms. Since neighboring group participation in the rate-determining step is an essential feature leading to the formation of a nonclassical intermediate, this explanation of the observed isotope effect for III and III-d_2 may be regarded as compatible with, though not a proof of, the formation of a nonclassical norbornyl cation in the solvolysis of III, as depicted below.[18]



In the acetolysis of II and II-d_2, an appreciable isotope effect of 1·05–1·07 was observed (Table 1). No analysis on the solvolysis product of the *p*-nitrobenzenesulphonate II has yet been carried out; but it has been reported very recently that acetolysis of 2-(Δ^2-cyclopentenyl)ethyl *p*-bromobenzenesulphonate, in the presence of sodium acetate, gave only the unrearranged product without the formation of any bicyclic materials.[19] Such a finding suggests that the Δ^2-double bond of the 2-(Δ^2-cyclopentenyl)ethyl system does not readily participate in acetolysis. This lack of participation is also supported by the fact that there is no rate enhancement in solvolyses of II as compared to I. Actually, the rate of a given solvolysis of II is somewhat slower than that of I (Tables 1 and 2), and this probably is due to a modest electron withdrawing inductive effect of the double bond in II.[19] Although participation of the double bond likely does not take place extensively, solvolyses of II may still possess greater carbonium ion character than solvolyses of I, thus accounting for the small, but appreciable, isotope effects observed for II and II-d_2.

Comparing the isotope effect data derived from the two solvent systems used in the present investigation (Table 1), a trend is apparent indicating that hydrolysis in aqueous dioxane tends to give a smaller, though only slightly smaller, isotope effect than acetolysis. This observation is also consistent with Streitwieser's treatment, which predicts that greater solvent participation will result in a lower α-deuterium kinetic isotope effect.

[18] The equilibrating nonclassical structures are included to indicate the occurrence of further hydride shifts suggested by preliminary results obtained in this laboratory from experiments with ^{14}C-labelled III.

[19] W. D. Closson and G. T. Kwiatkowski, *J. Amer. Chem. Soc.* **86**, 1887 (1964).

From the discussions presented so far, it is evident that solvolyses of I, II and III may be placed within the graded range of mechanisms for nucleophilic substitution on saturated carbon, with the nucleophilic or S_N2 solvolysis and the limiting or S_N1 solvolysis as the two extremes. The isotope effects strongly suggest more S_N2 character for the solvolysis of I. The question arises as to whether the use of the relative rates of III and I[3,4] will accurately measure the anchimeric assistance for III. If solvent participation were to cause an increase in rate over that of a reaction involving the open classical carbonium ion, the anchimeric assistance in the solvolysis of III may actually be greater than indicated by the solvolysis rate of III relative to that of I.

From a study on the dependence of solvolysis rates upon solvent changes, Bartlett[20] has ranked 2-cyclopentylethyl and 2-(Δ^3-cyclopentenyl)ethyl *p*-toluenesulphonates with isopropyl bromide and t-butyl chloride, respectively, in their response to the nucleophilic character of the solvent. The more favorable (less negative) entropies of activation of III as compared to those of I (Table 2) have been interpreted by Bartlett[20] as indicating a shift of III to internal solvation as opposed to external solvation in I. In other words, the more favourable $\Delta S^{\ddagger}$ of III may be explained on the basis that less fixation of solvent molecules in the transition state is required since the positive charge can be distributed internally because of the participation of the double bond in III (see also Ref. 13, p. 134). These observations further strengthen the belief that acetolysis of III is limiting and that the observed isotope effects for III and III-d_2 are in agreement with prediction from the suggestion of Streitwieser that a participating group may act as an entering group in lowering the magnitude of the α-deuterium kinetic isotope effect.

In Streitwieser's theoretical treatment,[12] the assumptions made led to the conclusion that the difference in rate as result of α-deuterium substitution is predominantly due to changes in zero point energy. The present results on the influence of temperature on k_H/k_D indicate that for the present systems studied over the temperature ranges employed, there is very little variation in k_H/k_D with changes in temperatures. The differences between the activation parameters for I, II and III and their corresponding dideuterated compounds are very small (Table 2) and the 95% confidence limits for these quantities are such that conclusions regarding such small differences cannot be drawn without reservation. Nevertheless, the data in Table 2 do hint at a possible trend that, with the exception of the solvolysis of II and II-d_2 in aqueous dioxane, an increase in the enthalpy of activation may be largely responsible for the rate retardation resulting from α-deuterium substitution. Leffek *et al.*[21] have treated temperature effects by plotting $\log (k_H/k_D)$ against reciprocals of absolute temperature, and from the slope and intercept, $\Delta\,\Delta H^{\ddagger}$ ($\Delta H_D^{\ddagger} - \Delta H_H^{\ddagger}$) and $\Delta\,\Delta S^{\ddagger}$($\Delta S_D^{\ddagger} - \Delta S_H^{\ddagger}$) were calculated. When the present kinetic data and isotope effects from solvolyses of III and III-d_2 were recalculated to include one extra figure and then treated by the method of Leffek *et al.*, the results obtained are shown in Table 3. Although the 95% confidence limits for the evaluated $\Delta\,\Delta H^{\ddagger}$ and $\Delta\,\Delta S^{\ddagger}$ are rather large, if these values were regarded as having some statistical significance, the results, as well as the data in Table 2, would suggest that apparently $\Delta\,\Delta H^{\ddagger}$ contributes more than $T\Delta\,\Delta S^{\ddagger}$ to $\Delta\,\Delta F^{\ddagger}$. This conclusion is consistent with the assumption that α-deuterium isotope effects in solvolytic reactions may be predominantly due to differences in zero point energy.

[20] P. D. Bartlett, Private communications.

[21] K. T. Leffek, R. E. Robertson and S. E. Sugamori, *Canad. J. Chem.* **39**, 1989 (1961).

TABLE 1. SPECIFIC RATE CONSTANTS AND KINETIC ISOTOPE EFFECTS IN SOLVOLYSES OF 2-CYCLOPENTYLETHYL, 2-(Δ^3-CYCLOPENTENYL)ETHYL AND 2-(Δ^3-CYCLOPENTENYL)ETHYL *p*-NITROBENZENESULPHONATES (I, II AND III, RESPECTIVELY) AND THEIR 1,1-DIDEUTERATED ANALOGUES (I-d_2, II-d_2 AND III-d_2, RESPECTIVELY)

Compound	In 25% water-75% dioxane			k_H/k_D	In glacial acetic acid			k_H/k_D
	Temp (°C)	10^6k_H (sec^{-1})	10^6k_D (sec^{-1})		Temp (°C)	10^6k_H (sec^{-1})	10^6k_D (sec^{-})	
I and I-d_2	40·50	5·17 ± 0·05	5·12 ± 0·04	1·01	60·65	1·10*	1·07*	1·03
	50·20	13·9 ± 0·1	13·8 ± 0·1	1·01	65·05	1·79 ± 0·01	1·74 ± 0·02	1·02
	60·65	37·3 ± 0·2	37·3 ± 0·1	1·00	75·00	5·04 ± 0·03	4·92 ± 0·06	1·02
	60·65	37·1 ± 0·2	36·9 ± 0·1	1·01	85·00	13·6 ± 0·1	13·5 ± 0·2	1·01
					85·05	13·9 ± 0·1	13·6 ± 0·1	1·02
II and II-d_2	40·50	4·71 ± 0·02	4·53 ± 0·02	1·04	60·65	1·02*	0·95*	1·07
	50·20	12·8 ± 0·1	12·4 ± 0·1	1·03	65·05	1·67 ± 0·02	1·56 ± 0·01	1·07
	60·65	34·6 ± 0·4	33·2 ± 0·3	1·04	75·00	4·56 ± 0·08	4·35 ± 0·04	1·05
	60·65	34·9 ± 0·3	33·2 ± 0·2	1·05	85·05	12·8 ± 0·2	12·2 ± 0·2	1·05
					85·05	12·7 ± 0·2	12·0 ± 0·1	1·06
III and III-d_2	40·50	19·7 ± 0·1	17·5 ± 0·1	1·13	40·50	10·7 ± 0·1	9·30 ± 0·12	1·15
	50·20	54·6 ± 0·6	48·7 ± 0·8	1·12	50·20	31·0 ± 0·4	27·2 ± 0·4	1·14
	60·65	151·2 ± 2·8	135·5 ± 1·7	1·12	60·65	93·9 ± 2·2	83·2 ± 1·5	1·13
	60·65	151·8 ± 2·0	135·2 ± 1·6	1·12	60·65	93·5 ± 2·0	82·4 ± 1·1	1·14

* Extrapolated values.

TABLE 2. RELATIVE RATES AND ACTIVATION PARAMETERS FROM SOLVOLYSES OF VARIOUS *p*-NITROBENZENESULPHONATES AT 60–65°

Compound	Relative rate		$\Delta H^{\ddagger}$ (kcal/mole)		$\Delta S^{\ddagger}$ (cal/deg/mole)	
	In H_2O–dioxane	In HOAc	In H_2O–dioxane	In HOAc	In H_2O-dioxane	In HOAc
I	34·0	1·00	19·75 ± 0·20	23·97 ± 0·51	−19·9 ± 0·6	−14·3 ± 1·5
I-d_2			19·79 ± 0·23	24·05 ± 0·35	−19·8 ± 0·7	−14·0 ± 1·0
II	31·7	0·93	19·99 ± 0·18	23·89 ± 0·79	−19·3 ± 0·5	−14·6 ± 2·4
II-d_2			19·92 ± 0·28	24·09 ± 0·52	−19·6 ± 0·8	−14·2 ± 1·6
III	138	85·6	20·42 ± 0·12	21·85 ± 0·17	−15·1 ± 0·8	−11·7 ± 0·5
III-d_2			20·51 ± 0·20	21·99 ± 0·17	−15·0 ± 0·6	−11·6 ± 0·5

TABLE 3. INFLUENCE OF TEMPERATURE ON THE ISOTOPE EFFECTS IN SOLVOLYSES OF III AND III-d_2

Temp (°C)	k_H/k_D	
	In H_2O–dioxane	In HOAc
40·50	$1·13_1$	$1·14_8$
50·20	$1·11_9$	$1·13_9$
60·65	$1·11_6$	$1·12_9$
60·65	$1·12_2$	$1·13_5$
$\Delta\Delta H^{\ddagger}$ (cal/mole)	96 ± 117	145 ± 67
$\Delta\Delta S^{\ddagger}$ (cal/deg/mole)	0·07 ± 0·009	0·19 ± 0·005

EXPERIMENTAL

Diethyl Δ^3-cyclopentenylmalonate. Diethyl malonate (48·0 g, 0·30 mole) was added to a solution of sodium ethoxide in ethanol (4·83 g Na in 150 ml dry ethanol) in a 3-necked flask equipped with stirrer, dropping funnel and reflux condenser fitted with a Drierite tube. The mixture was refluxed 5 min, cooled, and then 29·2 g (0·20 mole) 4-bromocyclopentene[16] was introduced with stirring. The reaction mixture was stirred and refluxed for 2 hr and then neutralized carefully with acetic acid. The ethanol was distilled off. After cooling, 125 ml water was added and the material extracted 4 times with 50-ml portions benzene. The combined extract was washed with water and dried ($MgSO_4$).

After distilling off the benzene using the water aspirator, the residue was fractionated under red. press. The excess diethyl malonate was recovered at 76–82° at 5 mm and 28·0 g (62%) diethyl Δ^3-cyclopentenylmalonate was collected at 117–120° at 4 mm. (Found: C, 63·35; H, 8·03. Calc. for $C_{12}H_{18}O_4$: C, 63·70; H, 8·02%).

Δ^3-Cyclopentenylmalonic acid. To 100 ml of a 25% KOH aq in a 500 ml flask equipped with magnetic stirrer was added 25·0 g (0·11 mole) diethyl Δ^3-cyclopentenylmalonate. The mixture was heated at 50° with stirring for 12 hr and then stirred overnight at room temp. The ethanol was removed by means of a rotatory evaporator. The residue was poured into cracked ice, acidified with 60 ml 50% H_2SO_4 aq, and then extracted 3 times with 50-ml portions ether. The combined extract was washed with sat NaCl aq and dried ($MgSO_4$). The ether was evaporated and the residue crystallized from ether–pet. ether. The yield of Δ^3-cyclopentenylmalonic acid, m.p. 153–154° dec (lit.[3] m.p. 149–150° dec) was 17·5 g (94%). (Found: C, 56·22; H, 5·93. Calc. for $C_8H_{10}O_4$: C, 56·46; H, 5·92%.)

Δ^3-Cyclopentenylacetic acid. A solution of 17·1 g (0·10 mole) of Δ^3-cyclopentenylmalonic acid in 150 ml pyridine was refluxed gently for 2·5 hr when no more CO_2 was given off [$Ba(OH)_2$ test]. The pyridine was removed under red. press. by a rotatory evaporator. The residue was poured over cracked ice, acidified with 20% H_2SO_4 aq and then extracted continuously for 12 hr with alcohol-free ether. After drying ($MgSO_4$), the ether was fractionated off and the residue distilled under red. press. The yield, b.p. 92–94° at 2 mm, was 11·0 g (87%).

Δ^3-Cyclopentenylacetic acid was obtained from decarboxylation of a commercial sample of Δ^3-cyclopentenylmalonic acid in the same manner as described above for the Δ^3-analog. An 82% yield, b.p. 96-97° at 7 mm (lit[22] b.p. 95–100° at 10 mm), was obtained.

Reduction of the substituted acetic acids. The cyclopentylacetic, Δ^2-cyclopentenylacetic and Δ^3-cyclopentenylacetic acids were reduced in the conventional way with either $LiAlH_4$ or $LiAlD_4$ in anhydrous ether. The alcohols obtained were 2-cyclopentylethanol, b.p. 82–84° at 18 mm (lit[3] b.p. 79–82° at 10 mm); 2-(Δ^2-cyclopentenyl)ethanol, b.p. 74–78° at 4 mm (lit[22] b.p. 86–87° at 16 mm); 2-(Δ^3-cyclopentenyl)ethanol, b.p. 80–82° at 3 mm (lit[3] b.p. 180–182°); 2-cyclopentylethanol-1,1-d_2, b.p. 72–74° at 10 mm; 2-(Δ^2-cyclopentenyl)ethanol-1,1-d_2, b.p. 66–68° at 3 mm; and 2-(Δ^3-cyclopentenyl)ethanol-1,1-d_2, b.p. 68–70° at 2 mm. The yields ranged from 68 to 97%. The NMR spectra of these alcohols showed that the triplets attributable to the methylene protons at C-1 essentially disappeared in the deuterated analogs.

The p-*nitrobenzenesulphonates* were prepared from the various alcohols by treatment with *p*-nitrobenzenesulphonyl chloride in pyridine solution. The products obtained were 2-cyclopentylethyl *p*-nitrobenzenesulphonate (I), m.p. 74° (lit[3] m.p. 74–75°); 2-cyclopentylethyl-1,1-d_2 *p*-nitrobenzenesulphonates (I-d_2), m.p. 75°; 2-(Δ^2-cyclopentenyl)ethyl *p*-nitrobenzenesulphonate (II), m.p. 63–64°, (Found: C, 52·48; H, 5·31; N, 4·60; S, 10·55. $C_{13}H_{15}O_5NS$ require: C, 52·51; H, 5·09; N, 4·71; S, 10·78%); 2-(Δ^2-cyclopentenyl)ethyl-1,1-d_2 *p*-nitrobenzenesulphonate (II-d_2), m.p. 64°; 2-(Δ^3-cyclopentenyl)ethyl *p*-nitrobenzenesulphonate (III), m.p. 64–65° (lit[3] m.p. 65–67°); and 2-(Δ^3-cyclopentenyl)ethyl-1,1-d_2 *p*-nitrobenzenesulphonate (III-d_2), m.p. 65–66°. The yields ranged from 65 to 77%. Details of a typical preparation are given below.

To a solution of 3·42 g (0·030 mole) 2-(Δ^3-cyclopentenyl)ethanol-1,1-d_2 in 30 ml dry pyridine cooled at −10°, 7·30 g (0·033 mole) *p*-nitrobenzenesulphonyl chloride was added. The mixture was stirred for 1 hr and then poured into a solution of 30 ml conc HCl in 150 ml ice-water. The precipitated crude product was collected by suction filtration and dried in a desiccator. The filtrate was extracted 3 times with ether. The combined extract was washed with water and dried ($MgSO_4$). After removal of the ether, the residue was combined with the original solid product and recrystallized from ether–pet. ether to give 6·70 g (74%) 2-(Δ^3-cyclopentenyl)ethyl-1,1-d_2 *p*-nitrobenzenesulphonate, m.p. 65–66°.

Kinetic studies. Solvolyses of various *p*-nitrobenzenesulphonates were carried out at different temps either in 25% water–75% dioxane (by volume) or in glacial acetic acid (Canadian Industries Limited, reagent, minimum 99·8% CH_3COOH). The initial concentration in each case was 0·05 M. To minimize possible errors due to variations between experiments, at each temp, corresponding protio- and deuterio-compounds were solvolyzed simultaneously. The rates were followed by titration of the sulphonic acid liberated.[23,24] For hydrolysis in aqueous dioxane, 0·02N NaOH (British

[23] C. R. Noller and R. Adams, *J. Amer. Chem. Soc.* **48**, 2444 (1926).
[24] S. Winstein, E. Grunwald and L. L. Ingraham, *J. Amer. Chem. Soc.* **70**, 827 (1948).
[24] S. Winstein and H. Marshall, *J. Amer. Chem. Soc.* **74**, 1120 (1952).

Drug House, reagent, carbonate-free) was used, with methyl red as indicator. For acetolysis, 0·02N sodium acetate in glacial acetic acid was employed, with bromphenol blue as indicator.

The specific rate constants, k, were evaluated from the slopes of log $(a/a - x)$ vs t; the activation parameters, $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$, were calculated using the slopes of log k vs $1/T$; and $\Delta\,\Delta H^{\ddagger}$ and $\Delta\,\Delta S^{\ddagger}$ were derived from the slopes and intercepts of log k_H/k_D vs $1/T$. These plots were obtained by the least squares methods with the aid of a digital computer, and their standard deviations were also evaluated by the computer.[25] The 95% confidence limits for the results shown in Tables 1, 2 and 3 were calculated by multiplying the standard deviations by 1·96.[26]

Acknowledgments—We wish to extend our thanks to Professor P. D. Barlett for supplying us with the procedure for the preparation of 4-bromocyclopentene before its publication, to Professors Bartlett and Streitwiesser for valuable comments on some of our results and to the National Research Council of Canada for financial support.

[25] All computer programming were kindly worked out by Professor N. Shklov of the Mathematics Department.

[26] Jerome C. R. Li. *Introduction to Statistical Inference* Chap. 11. Edward Brothers, Michigan (1957).