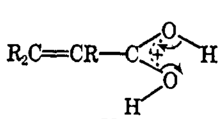
Table III. Activation Parameters Calculated at 0°

	$\Delta H^{\ddagger}$ [a]	$\Delta S^{\ddagger}$ [b]	No. of points on plot
$CH_3CO_2H_2^+$ [c]	16.3	−13.1	5
$(CH_3)_2C{=}CHCO_2H_2^+$	16.7	−8.8	4
$CH_2{=}CH(CH_3)CO_2H_2^+$	19.0	+1.7	5
$CH_3CH{=}CHCO_2H_2^+$	19.8	+3.7	4

[a] $\Delta H = E_a - RT$ (kcal/mole). [b] $\Delta S = 4576 \log A/T - 49.203$; time in seconds and entropy in standard units (eu). [c] From ref 3c.

rates of cleavage compared to that of protonated acetic acid under the same conditions are given in Table II.

From the rate of cleavage and activation parameters (the Arrhenius parameters are summarized in Table III), little could be said about the transition states. A cyclic symmetrical transition state V as proposed for the acidolysis of esters[7] is also likely for the dehydration of protonated unsaturated carboxylic acids.



V

Experimental Section

Materials. All alkenoic acids were commercial materials of reagent grade and were used without further purification.

Nmr Spectra. Varian Associates Model A-56/60A and HA 60-IL nmr spectrometer with variable-temperature probes were used for all spectra. The coupling constants are accurate to within 0.1 Hz.

Preparation of Protonated Acids. Samples of protonated acids were prepared by dissolving 1.5 ml of SbF_5-FSO_3H (1:1 *M*) in an equal volume of sulfur dioxide and cooling to −78°. The acid (~0.3 g) was dissolved in 2 ml of sulfur dioxide, cooled to −78°, and dropwise added to the acid solution. The kinetics were measured using the published procedure for the carboxylic acids.[3c] The excess of acid (SbF_5-FSO_3H) indicated by the intense peaks at −10.9 ppm and that of H_3O^+ at −10.5 ppm were deleted from the spectra for simplicity (Figures 1-5).

Acknowledgment. Support of the work by a grant of the National Institutes of Health is gratefully acknowledged.

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Kinetics of Reactions of 2-Hexyl Halides and 2-Hexyl *p*-Bromobenzenesulfonate with Sodium Methoxide in Methanol. Evidence That Orientation of Olefin-Forming Elimination Is Not Determined by the Steric Requirements of Halogen Leaving Groups[1,2]

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Contribution from the Metcalf Chemical Laboratories, Brown University, Providence, Rhode Island. *Received August 28, 1967*

Abstract: The kinetics of the elimination and substitution reactions of $NaOCH_3$ with the four 2-hexyl halides and 2-hexyl *p*-bromobenzenesulfonate have been measured by a precise gas–liquid partition chromatographic technique, and activation parameters have been evaluated. The 2-hexenes:1-hexene ratio diminishes steadily from iodine to fluorine, and 1-hexene is the predominant olefin from 2-hexyl fluoride. The 2-hexene *trans*:*cis* ratio diminishes steadily in the same order. These effects are in accord with the theory of the variable E2 transition state, but cannot be attributed to steric repulsions between the (solvated) leaving group and β-alkyl substituents. Novel linear free energy relationships obtain, for all the 2-hexyl halides, between log *k*(1-hexene) and log *k*(*cis*-2-hexene) or log *k*(*trans*-2-hexene), but the data for 2-hexyl brosylate do not conform to these relationships.

Recent observations have challenged theories of orientation in olefin-forming elimination that had enjoyed wide if not universal acceptance. Saunders's discovery that 2-fluoropentane forms mainly 1-pentene on reaction with sodium ethoxide in ethanol[5] is difficult to reconcile with the hypothesis[6,7] that Hofmann orientation[8] is determined by steric interactions. Demonstration that orientation may be drastically changed, and indeed reversed, by varying the base–solvent system[10,11] contradicts the theory[12,13] that Hofmann

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(1) Based on the Ph.D. Dissertation of R. A. Bartsch, June 1967. This dissertation will be abstracted by *Dissertation Abstracts*, and copies will be available from University Microfilms, Ann Arbor, Mich.

(2) 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 this fund.

(3) Jesse M. Metcalf Fellow, 1964–1965; ICI (Organics) Fellow, 1965–1966.

(4) University of California, Santa Cruz, Calif.

(5) W. H. Saunders, Jr., S. R. Fahrenholtz, E. A. Caress, J. P. Lowe, and M. Schreiber, *J. Am. Chem. Soc.*, **87**, 3401 (1965).

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(8) When H and X are eliminated from adjacent carbons to form a double bond, the carbon which carries leaving group X is designated α, and those adjacent to it β. Formation of the double bond toward the less substituted β-carbon is known as *Hofmann* orientation, while elimination toward the more substituted β-carbon is called *Saytzeff* orientation.[9]

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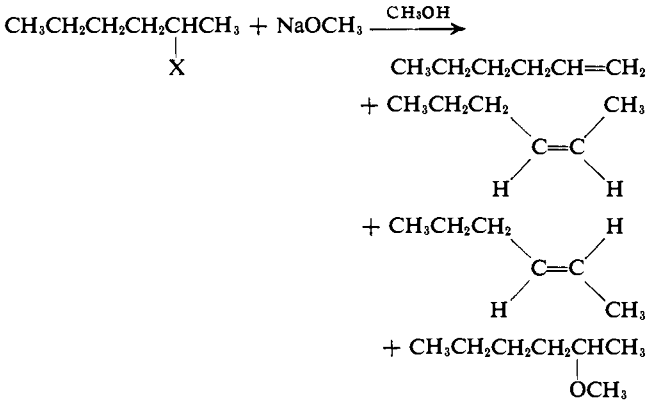
orientation is determined by the polarity of the leaving group and its effect on the acidity of the β-hydrogens.

These are questions of *positional* orientation. *Geometrical* orientation, concerning the proportions in which isomeric *cis* and *trans* olefins are formed from a common substrate, has also become a subject of interest. Consistent trends in the *trans*:*cis* ratio with change in the leaving group have been reported,[5,7,14] although one recent paper[7] offered no comment on the trend despite the fact that the general principles involved had earlier been indicated by Bunnett[9] and applied to specific data by Banthorpe.[15]

Another problem in geometrical orientation concerns the fact that 2-butyl and 2-pentyl tosylates afford more *cis*- than *trans*-2-alkene on treatment with potassium *t*-butoxide in *t*-butyl alcohol, although the *trans* isomer predominates with potassium ethoxide in ethanol or when either base is employed in dimethyl sulfoxide solution.[16,17]

Nearly all of the results cited above are from studies in which products were determined without measurement of reaction rates. It was apparent that a thorough kinetic study would provide a better basis for interpretation. Accordingly the present investigation was undertaken.

We have studied the kinetics of the three elimination reactions and the competing substitution which occur on treatment of all four 2-hexyl halides and 2-hexyl *p*-bromobenzenesulfonate (brosylate) with sodium methoxide in methanol. The 2-substituted hexane system was chosen for reasons of convenience in analysis and because not even a thorough product study had previously been made.



In their great pioneering researches on elimination reactions, Hughes and Ingold and their collaborators determined the kinetics of several E2 reactions, including some of *sec*-alkyl halides.[18] The substrates studied included isopropyl chloride, bromide, and iodide, *sec*-butyl bromide, and 2- and 3-bromopentanes. They determined the per cent olefin product by a bromimetric titration method but did not attempt to assess the proportions of *cis*- and *trans*-2-butenes or 2-pentenes. The advent of gas–liquid partition chromatography (glpc) has made it feasible to carry out precise rate studies on the concurrent formation of several isomeric olefins such as would scarcely have been possible in earlier years.

Colter and coworkers[19] have studied the kinetics of elimination from two series of *sec*-alkyl arenesulfonates.

Materials and Methods. The methods of synthesis were chosen so as to afford the desired 2-hexyl halides from 2-hexanol without concomitant formation of isomeric halides.[20] The corresponding 1- and 3-hexyl halides were independently prepared, and it was shown that the 2-hexyl halide preparations were uncontaminated by isomers. Preparation of the brosylate was straightforward.

Reactions were carried out under conditions conducive to pseudo-first-order kinetics and were followed by glpc. This procedure enabled monitoring of the product ratio throughout each run. Formation of all products was found to be kinetically controlled; no interconversion of products occurred under reaction conditions. A few runs were also followed by titration methods, with concordant results.

Experimental Section

Materials. 2-Iodohexane. According to the procedure of Wiley, *et al.*,[21] a solution of 2-hexanol and triphenylphosphorus in dimethylformamide was treated with iodine. After steam distillation of the reaction mixture, the distillate was extracted with pentane and the pentane layer was washed with water, dried over $MgSO_4$, and evaporated *in vacuo*. The residual liquid was chromatographed on alumina using pentane as eluent. The eluted pentane solution was evaporated *in vacuo* and the remaining liquid was fractionally distilled under reduced pressure yielding 16% of clear, colorless liquid, bp 50.5–51° (12 mm) (lit.[22] 45.0–45.6 (9 mm)), n^{25}D 1.4896 (lit. n^{25}D 1.4911,[23] 1.4878[22]). The infrared spectra of 2-iodohexane prepared by this method and by the more conventional reaction of 2-hexyl *p*-toluenesulfonate with an inorganic iodide were indistinguishable. *Anal.* Calcd for $C_6H_{13}I$: C, 33.98; H, 6.18. Found:[24] C, 34.02; H, 6.24.

3-Iodohexane for physical property comparisons was prepared in 28% yield in the same manner and had bp 48–49° (11 mm), n^{25}D 1.4926. *Anal.* Calcd for $C_6H_{13}I$: C, 33.98; H, 6.18. Found:[24] C, 34.17; H, 6.32.

2-Bromohexane was prepared by the same procedure as 2-iodohexane, except that bromine was used instead of iodine. The colorless liquid (21% yield) had bp 142–143° (lit.[25] 143.6–144.1°), n^{25}D 1.4421 (lit.[26] n^{25}D 1.4432), and was shown to be isomer free by glpc. *Anal.* Calcd for $C_6H_{13}Br$: C, 43.66; H, 7.94. Found:[24] C, 43.79; H, 8.01.

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3-Bromohexane was synthesized in 28% yield by the above procedure and had bp 143–144° (lit.[27] 141–142°), $n^{25}\mathrm{D}$ 1.4461 (lit.[27] $n^{20}\mathrm{D}$ 1.4450).

2-Chlorohexane was prepared by the procedure of Bunnett, *et al.*,[28] for α,α-dideuteriobenzyl chloride except that the order of addition of reactants was reversed. A 19% yield of 2-chlorohexane was obtained; bp 123–123.5° (lit.[29] 122–123°), $n^{22}\mathrm{D}$ 1.4110 (lit.[29] $n^{21.5}\mathrm{D}$ 1.4153); demonstrated to be isomer free by gas chromatography. *Anal.* Calcd for $C_6H_{13}Cl$: C, 59.74; H, 10.86. Found:[24] C, 59.44, 59.59; H, 10.95, 11.06.

3-Chlorohexane was synthesized by a Darzen's procedure.[30] The clear, colorless liquid (26% yield) had bp 115–116° (lit.[27] 59.5–60° (95 mm)), $n^{25}\mathrm{D}$ 1.4148 (lit.[27] $n^{20}\mathrm{D}$ 1.4163).

2-Fluorohexane was made from 2-hexyl benzenesulfonate by the method of Bergmann and Shahek.[31] The distillate was subjected to preparative glpc on a 0.5 in. × 10 ft column of 15% Carbowax 20M on Chromosorb P at 25° to separate the 2-fluorohexane from accompanying hexenes. The colorless liquid (9% yield) had (micro) bp 85° (lit.[32] 86.1–86.2°), $n^{27.5}\mathrm{D}$ 1.3670 (lit.[32] $n^{20}\mathrm{D}$ 1.3693), and was demonstrated to be isomer free and homogeneous by glpc. The proton magnetic resonance spectrum of 2-fluorohexane was complex because of splitting by both protons and fluorine. The spectrum exhibited two apparent sextets centered at τ 5.57 (2-CH) and two doublets centered at τ 8.77 (1-CH_3) which were superimposed upon a complex multiplet from τ 8.0 to 9.3 (all other protons). The coupling constant, J_{H-F}, was about 49 cps for the interaction between F and 2-CH and about 23 cps for the interaction between F and 1-CH_3. Coupling between 1-CH_3 and 2-CH protons occurred with $J_{H-H} = 6.2$ cps. The spectrum was in excellent agreement with a calculated spectrum of 2-fluorohexane[33] and a reported spectrum of 2-fluoropentane.[5] *Anal.* Calcd for $C_6H_{13}F$: C, 69.18; H, 12.58. Found:[34] C, 68.50; H, 12.60.

3-Fluorohexane. The preparation of 3-fluorohexane was attempted by the procedure of Bergmann, *et al.*[35] Separation of the hexenes from "fluorohexane" in the trapped liquid was accomplished by preparative glpc. The "fluorohexane" was shown by glpc to be a mixture of 3-fluorohexane (~90%) and 2-fluorohexane (~10%).

2-Hexyl *p*-Bromobenzenesulfonate was prepared from 2-hexanol and *p*-bromobenzenesulfonyl chloride by the general procedure of Kochi and Hammond.[36] Recrystallization from ether–pentane (50:50 v/v) afforded the ester in 95% yield; mp 35–36°. *Anal.* Calcd for $C_{12}H_{17}BrO_3S$: C, 44.86; H, 5.33. Found:[24] (1) C, 45.13; H, 5.30; (2) C, 45.05; H, 5.47.

2-Hexyl methyl ether was synthesized from the sodium alcoholate of 2-hexanol and dimethyl sulfate by the method of Marks, *et al.*[37] Distillation through a spinning-band column gave a 17% yield of clear, colorless liquid, bp 110–111°, $n^{27.5}\mathrm{D}$ 1.3918, which was homogeneous to glpc analysis on a 0.25 in. × 5 ft column of 15% SF-96 on Firebrick operated at 80°. *Anal.* Calcd for $C_7H_{16}O$: C, 72.35; H, 13.92. Found:[24] C, 71.81; H, 13.72.

Gas–liquid partition chromatographic analyses were performed either on an Aerograph Model A-90-P thermal conductivity gas chromatograph (0.25-in. columns) or a Model 204 flame ionization gas chromatograph (0.125-in. columns). The solid support was Chromosorb P.

The 1-, 2-, and 3-bromohexanes were separated on a 0.25 in. × 20 ft column of 15% Carbowax 20M at 80°. A 0.25 in. × 11 ft column of 15% Bentone 34-5% SE-30 operated at 100° served to separate 1-, 2-, and 3-chlorohexanes. The isomeric 1-, 2-, and 3-fluorohexanes were separated on a 0.125 in. × 30 ft column of 20% Ucon 50HB100 at ambient temperatures. A separation of 2- and 3-iodohexanes could not be achieved although a large number of columns were tried.

Glpc analysis of the elimination products (1-hexene, *trans*-2-hexene, and *cis*-2-hexene) and *n*-hexane (internal standard) was performed on 0.125 in. × 30 ft columns of 20% Ucon 50HB100 operated at ambient temperatures. For analysis of the substitution product (2-hexyl methyl ether) and toluene (internal standard), the same columns were used at 100°. To prevent contamination of these columns with sodium methoxide, glass inserts filled with glass wool were placed in the injection ports of the flame ionization gas chromatograph.

The molar responses of 1-hexene, *trans*-2-hexene, and *cis*-2-hexene (API standards) relative to *n*-hexane (Phillips, 99.99%) were all within experimental error of unity. The molar response of prepared 2-hexyl methyl ether to toluene (Mallinckrodt, analytical reagent) was determined to be 0.861 ± 0.009.

Product Analysis by Glpc. A. Olefin Product Studies. By the glpc procedures employed for the kinetic studies, except that in some instances no internal standard was added, the relative proportions of 1-hexene, *trans*-2-hexene, and *cis*-2-hexene from reactions of the 2-hexyl halides and 2-hexyl brosylate with sodium methoxide in methanol were determined. Since no molar response corrections were necessary, the relative areas under the cleanly separated hexene peaks directly reflected the relative concentrations of the three hexenes. For the brosylate, only olefinic product ratios from infinity samples were used because of analytical difficulties resulting from reaction of unconsumed ester with sodium methoxide on the glass wool in the injector inserts.

The relative proportions of hexenes formed in the methanolysis of 2-hexyl brosylate were determined in similar fashion, except for the manner of preparation of the reaction solutions. (See kinetic studies of the methanolysis of 2-hexyl brosylate.)

B. **Per Cent Elinination Investigations.** Solutions of *n*-hexane (internal standard) and the 2-substituted hexane (both 0.1–0.5 *M*) in sodium methoxide in methanol (0.6–2.0 *M*) were prepared by drawing the substrate (except 2-hexyl brosylate) and the internal standard into tared vessels fashioned from thin-walled glass tubing reduced to capillaries on each end. The vessels were weighed, dropped into the cooled methanolic solution, and crushed with a glass rod. After mixing, 1.0-ml samples were withdrawn, sealed in ampoules, and placed in a thermostat for at least ten half-lives. Analysis was performed by direct injection of a 1-μl portion of the contents of an ampoule into the injection port of the Aerograph Model 204 gas chromatograph. Three or four samples were allowed to react at each temperature of interest. The per cent elimination was calculated by comparing the initial concentrations of substrate and internal standard with the peak areas under the hexene and *n*-hexane peaks.

C. **Per cent substitution studies** were carried out as above with toluene as internal standard. Molar response corrections were applied to the relative areas of the 2-hexyl methyl ether and toluene peaks before calculation of the per cent substitution.

Kinetic Measurements Employing Glpc Analysis of Reaction Products. A. Reactions with sodium methoxide in methanol were studied under conditions conducive to pseudo-first-order reactions (at least a tenfold excess of base). Samples (0.2–0.5 ml) of a reaction solution of *n*-hexane (internal standard), the 2-substituted hexane (both 0.01–0.08 *M*), and sodium methoxide in methanol[28] (0.6–2.0 *M*) were sealed in nitrogen-flushed ampoules. All the ampoules were placed in a thermostat at once and six to eight samples per run were removed at recorded times, plunged into ice water or Dry Ice–isopropyl alcohol (depending upon the reaction temperature), and kept cold until analysis. "Infinity" ampoules were removed after at least ten half-lives. Analysis was performed by injecting a 1-μl portion of the contents of an ampoule into the injection port of the Aerograph Model 204 gas chromatograph. Plots of log $\{[(\Sigma\text{hexene peak areas})/(n\text{-hexane peak area})]_\infty - [(\Sigma\text{hexene peak areas})/(n\text{-hexane peak area})]_t\}$ *vs.* time were uniformly linear. Slopes of these lines, as calculated by linear regression–least squares analysis, were multiplied by −2.303 to give the total pseudo-first-order rate coefficients.

B. **Methanolysis of 2-Hexyl Brosylate.** A solution of the 2-substituted hexane, 2,6-lutidine (sterically hindered base, present to suppress acid-catalyzed reactions of substrate or reaction products), and toluene (internal standard) was prepared. Concentrations were: 2-hexyl brosylate, 0.05–0.13 *M*; toluene, 0.05–0.23 *M*: 2,6-lutidine, 0.05–0.15 *M*. Progress of reaction was followed by the above ampoule procedure. Plots of log $\{[(\text{2-hexyl methyl ether peak area})/(\text{toluene peak area})]_\infty - [(\text{2-hexyl methyl ether peak area})/(\text{toluene peak area})]_t\}$ *vs.* time were linear.

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C. **Methanolysis of 2-Hexyl Halides.** Estimates of rates of methanolysis of the halides were obtained in a like manner; the ampoules were subjected to the highest temperature used in kinetic studies of the reactions with sodium methoxide in methanol for ten half-lives of the sodium methoxide reactions. In all cases, $<1\%$ of 2-hexyl methyl ether (major methanolysis product) was formed per half-life of the reaction with sodium methoxide. Thus, the rates of methanolysis were judged to be negligible when compared to the rates of reaction with sodium methoxide.

Confirmatory Kinetic Runs. A. By Titration of Liberated Iodide Ion. A solution of 2-hexyl iodide (0.083 *M*) and sodium methoxide (0.639 *M*) in methanol was prepared. Aliquots (5.00 ml) were sealed in nitrogen-flushed ampoules, placed in a 50.8° thermostat, and removed at recorded times as described above. The chilled contents were poured into distilled water. After extraction with two portions of carbon tetrachloride, the iodide ion in the aqueous layer was titrated with standard silver nitrate solution using a Radiometer automatic titrator. A plot of log [(milliliters of added $AgNO_3$ solution)$_\infty$ − (milliliters of added $AgNO_3$ solution)$_t$] *vs.* time was linear. Multiplying the slope by −2.303 gave a total pseudo-first-order rate coefficient of $(1.75 \pm 0.03) \times 10^{-4}$ sec^{-1}. This compares with $(1.80 \pm 0.03) \times 10^{-4}$ sec^{-1} interpolated from kinetic data obtained by the glpc method.

B. **By Acid–Base Titration.** A solution of 7.03 g of 2-hexyl brosylate and 0.639 *M* sodium methoxide in methanol was prepared in a 250-ml volumetric flask. After mixing, 25.00-ml samples were sealed in nitrogen-flushed ampoules, which were placed in the 50.8° thermostat all at once. Ampoules were removed at recorded times and plunged into Dry Ice–isopropyl alcohol. The ampoules were broken open and the contents were transferred quantitatively to flasks containing 50.00 ml of 0.682 *M* hydrochloric acid. The resulting mixture was extracted twice with carbon tetrachloride and the volume of the aqueous layer was adjusted to 120 ml with distilled water. A Radiometer automatic titrator was used to titrate the solution with 0.600 *M* sodium hydroxide. A plot of $-\log [(a - x)/(b - x)]$ *vs.* time was linear, where a = initial ester concentration, b = initial base concentration, $a - x$ = ester concentration at time t, $b - x$ = base concentration at time t. The slope was multiplied by $2.303/(a - b)$ to give a total second-order rate coefficient of $(1.07 \pm 0.09) \times 10^{-3}$ l. mole^{-1} sec^{-1}, which is compared to a value of $(1.04 \pm 0.01) \times 10^{-3}$ l. mole^{-1} sec^{-1} obtained by the glpc kinetic method.

Isomerization Studies. According to the usual procedures, solutions of 2-hexyl methyl ether and of 1-hexene with sodium methoxide in methanol were prepared. Samples were sealed in ampoules and subjected to the most forcing conditions employed. These were conditions endured by infinity samples in the reaction of 2-fluorohexane with 2.04 *M* sodium methoxide at 164.4°; the exposure time was 24 hr. Analysis by glpc showed that no hexenes were produced from 2-hexyl methyl ether. However, the 1-hexene was isomerized to a mixture of 94.9% 1-hexene, 1.1% *trans*-2-hexene, and 4.0% *cis*-2-hexene.

Kinetic Calculations. A. Reactions of 2-Hexyl Halides with Sodium Methoxide in Methanol. As described above, rates of methanolysis were negligible in comparison to over-all rates of reaction with sodium methoxide in methanol. Therefore, the total pseudo-first-order rate coefficients were equal to the sum of the individual pseudo-first-order rate coefficients for formation of the elimination and substitution products. The percentages of elimination and substitution and the relative proportions of the isomeric hexenes were known at each temperature of kinetic study. The pseudo-first-order rate coefficient for the formation of each product was evaluated by multiplying the total pseudo-first-order rate coefficient by the per cent product formed. Second-order rate constants were calculated by dividing the pseudo-first-order rate coefficients by the relevant sodium methoxide concentration (corrected for thermal expansion of methanol[38]).

Typical Kinetic Run and Dissection of Pseudo-First-Order Rate Coefficient. Reaction of 2-bromohexane with sodium methoxide in methanol gave the results shown in Table I; initial concentrations: RBr, 0.0448 *M*; *n*-hexane, 0.0185 *M*; CH_3ONa, 1.25 *M* (room temperature); RBr, 0.0429 *M*; *n*-hexane, 0.0177 *M*; CH_3ONa, 1.20 (at 59.8°); temperature 59.8°.

The plot of log $(R_\infty - R_t)$ *vs.* time was linear with slope $(-3.85 \pm 0.05) \times 10^{-3}$ min^{-1}; multiplied by $^{-2.303}/_{60}$, this gave a pseudo-first-order rate coefficient, k_ψ, of $1.48 \pm 0.02 \times 10^{-4}$ sec^{-1}. From product studies, the yields of the elimination and substitution products were determined to be 1-hexene, 16.4 ± 0.2%; *trans*-2-hexene, 42.8 ± 0.8%; *cis*-2-hexene, 12.0 ± 0.8%; and 2-hexyl methyl ether, 28.8 ± 0.8%. The pseudo-first-order rate coefficient for formation of each product was calculated by multiplying k_ψ by the per cent product formed. Division of the resulting coefficient by the sodium methoxide concentration gave the following second-order rate coefficients (all in l. mole^{-1} sec^{-1} × 10^5): 1-hexene, 2.01 ± 0.04; *trans*-2-hexene, 5.26 ± 0.13; *cis*-2-hexene, 1.48 ± 0.10; 2-hexyl methyl ether, 3.54 ± 0.11.

Table I

Time, min	R^a	$R_\infty - R_t$	$\log (R_\infty - R_t)$
0	0.051	2.398	0.380
20	0.439	2.010	0.303
40	0.781	1.668	0.222
62	1.090	1.359	0.133
80	1.270	1.179	0.072
102	1.474	0.975	−0.011
1266	2.446		
1266	2.453		

^{a} R = area of hexene peaks/area of *n*-hexane peaks.

B. **Reaction of 2-Hexyl Brosylate with Sodium Methoxide in Methanol.** For this substrate, rates of methanolysis were significant when compared to rates of reaction with sodium methoxide in methanol. However, product and kinetic studies of methanolysis and the reaction with sodium methoxide in methanol allowed both product proportions and rate coefficients to be sorted out as to the solvolytic and base-induced contributions to the formation of each product. The over-all pseudo-first-order rate coefficients for solvolysis ($k_\psi{}^S$) and for the total reaction with sodium methoxide in methanol ($k_\psi{}^T$) were multiplied by the fractional yields of product A (symbolizing any of the four products) in the respective reactions to obtain the partial pseudo-first-order coefficients, $(k_\psi{}^S)_A$ and $(k_\psi{}^T)_A$, for formation of product A under the two sets of conditions. Subtraction of $(k_\psi{}^S)_A$ from $(k_\psi{}^T)_A$ gave $(k_\psi{}^M)_A$, the partial pseudo-first-order coefficient pertaining to formation of A from reaction of the substrate with sodium methoxide. Division of $(k_\psi{}^M)_A$ by the sodium methoxide concentration gave the second-order coefficient for reaction of the substrate with sodium methoxide to form product A. Such values are tabulated in Table V. The yields of the various products as listed for "$NaOCH_3$ only (calcd)" in Table II are in proportion to the respective second-order rate coefficients.

C. **Activation Parameters.** $\Delta H^{\ddagger}$ was calculated from the slopes (determined by a computer programmed for linear-regression–least-squares analysis) of plots of log k_2 *vs.* $1/T$ and the equation $\Delta H^{\ddagger} = E_a - RT$. $\Delta S^{\ddagger}$ was calculated by the equation[39]

$$\Delta S^{\ddagger}/4.576 = \log k_2 - 10.753 - \log T + E_a/(4.576T)$$

Results

Products. Solvolysis of each of the 2-hexyl halides was shown to be negligible, under the conditions employed, compared to the rate of reaction with sodium methoxide. Product compositions can therefore be ascribed directly to reactions with the base. Our full data for 2-hexyl fluoride and representative data for the other halides are presented in Table II.[40]

On the other hand, solvolysis of 2-hexyl brosylate was appreciable under the conditions of the rate studies with sodium methoxide. It was necessary to correct the observed product compositions from reactions with methoxide solutions for the contribution of solvolysis. The correction procedure is discussed in detail in the Experimental Section. In Table III, we present observed product compositions at three temperatures from reactions both in the absence and in the presence of sodium methoxide, as well as calculated product compositions for the bimolecular reactions with sodium

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(38) J. M. Costello and S. J. Bowden, *Rec. Trav. Chim.*, 77, 36 (1958).

(39) J. F. Bunnett, "Investigation of Rates and Mechanisms of Reaction," Part I, S. L. Friess, E. S. Lewis, and A. Weissberger, Ed., 2nd ed, Interscience Publishers, Inc., New York, N. Y., 1961, p 201.

(40) Full data are presented in the dissertation of Bartsch.[1]

Table II. Products from Reactions of 2-Hexyl Halides with Sodium Methoxide in Methanol[a]

Halide	Temp, °C	No. of samples[b]	Na-OCH_3, *M*	1-Hexene, %	*trans*-2-Hexene, %	*cis*-2-Hexene, %	2-Hexyl methyl ether, %	**2:1**	*trans*:*cis*
Fluoride	129.5	4	2.04	46.5 ± 0.6	12.8 ± 0.3	5.4 ± 0.4	35.3 ± 0.8	0.39 ± 0.02	2.4 ± 0.2
	139.6	2	2.04	49.2 ± 0.1	13.1 ± 0.1	5.4 ± 0.1	32.3[c]	0.38 ± 0.01	2.4 ± 0.1
	139.6	6	2.04	49.2 ± 0.9	13.2 ± 0.4	5.3 ± 0.5	32.3[c]	0.38 ± 0.03	2.5 ± 0.2
	149.8	5	2.04	51.5 ± 0.6	13.5 ± 0.4	5.6 ± 0.5	29.4[c]	0.37 ± 0.02	2.4 ± 0.2
	149.8	5	2.04	51.4 ± 0.8	13.3 ± 0.5	5.9 ± 0.4	29.4[c]	0.37 ± 0.02	2.3 ± 0.1
	149.8	5	1.25	49.1 ± 0.4	14.3 ± 0.6	6.2 ± 0.6	30.4[d]	0.42 ± 0.02	2.3 ± 0.3
	164.4	3	2.04	55.5 ± 1.0	13.7 ± 1.0	5.6 ± 0.6	25.2 ± 0.3	0.35 ± 0.03	2.4 ± 0.3
Chloride	79.8	4	0.66	18.6 ± 0.4	32.8 ± 0.4	10.3 ± 0.2	38.3 ± 0.3	2.3 ± 0.1	3.2 ± 0.1
	98.8	3	0.66	21.5 ± 0.1	32.8 ± 0.1	10.2 ± 0.2	35.5 ± 0.5	2.00 ± 0.02	3.2 ± 0.1
	99.0	11	1.25	21.8 ± 0.3	32.3 ± 0.3	11.3 ± 0.3	34.6 ± 0.6	2.00 ± 0.04	2.9 ± 0.1
Bromide	59.8	8	0.64	16.0 ± 0.3	42.7 ± 0.3	12.2 ± 0.2	29.1 ± 0.1	3.4 ± 0.1	3.5 ± 0.1
	79.8	6	1.25	18.9 ± 0.7	42.6 ± 0.4	12.4 ± 0.4	26.1 ± 0.4	2.9 ± 0.1	3.4 ± 0.1
	79.8	8	0.64	18.5 ± 0.3	41.9 ± 0.4	12.4 ± 0.3	27.2 ± 0.4	2.9 ± 0.1	3.4 ± 0.1
	99.1	6	0.64	20.7 ± 0.2	40.9 ± 0.3	13.4 ± 0.3	25.0 ± 0.4	2.62 ± 0.02	3.1 ± 0.1
Iodide	44.3	7	0.64	10.7 ± 0.3	59.7 ± 0.3	13.6 ± 0.3	16.0 ± 0.5	6.9 ± 0.2	4.4 ± 0.1
	99.1	6	0.64	16.3 ± 0.3	52.9 ± 0.3	14.8 ± 0.1	16.0[e]	4.2 ± 0.1	3.6 ± 0.1

[a] Full data for 2-hexyl fluoride are presented, but only a selection of data for the other halides. Full data for the latter are listed in the dissertation of Bartsch.[1] The uncertainties listed are standard deviations. [b] For determination of olefin product ratios. [c] Interpolated value. [d] Interpolated value plus 1.0%, because of lower [$NaOCH_3$]. [e] Extrapolated value.

Table III. Products from Reactions of 2-Hexyl *p*-Bromobenzenesulfonate[a]

Temp, °C	$NaOCH_3$, *M*	Reaction	1-Hexene, %	*trans*-2-Hexene, %	*cis*-2-Hexene, %	2-Hexyl methyl ether, %	**2:1**	*trans*:*cis*
44.3	0.66	Total (obsd)	5.88 ± 0.02	8.39 ± 0.02	4.33 ± 0.02	81.4 ± 0.7		
		Solvolysis (obsd)	0.70 ± 0.03	5.88 ± 0.05	3.01 ± 0.06	90.4 ± 0.3	12.6 ± 0.8	1.95 ± 0.05
	0.66	$NaOCH_3$ only (calcd)	7.22 ± 0.19	8.93 ± 0.23	4.52 ± 0.12	79.3 ± 1.4	1.86 ± 0.08	1.98 ± 0.06
50.8	1.25	Total (obsd)	6.56 ± 0.04	8.30 ± 0.02	4.44 ± 0.06	80.7 ± 0.4		
	0.66	Total (obsd)	6.41 ± 0.02	8.92 ± 0.02	4.74 ± 0.06	79.9 ± 0.1		
		Solvolysis (obsd)	0.85 ± 0.03	6.48 ± 0.03	3.37 ± 0.02	89.3 ± 0.3	11.7 ± 0.7	1.92 ± 0.01
	1.25	$NaOCH_3$ only (calcd)	8.31 ± 0.23	9.20 ± 0.29	5.00 ± 0.17	77.5 ± 1.1	1.71 ± 0.02	1.84 ± 0.08
	0.66	$NaOCH_3$ only (calcd)	8.02 ± 0.16	9.32 ± 0.13	4.86 ± 0.09	77.8 ± 0.8	1.77 ± 0.05	1.92 ± 0.05
59.8	0.66	Total (obsd)	7.00 ± 0.11	9.39 ± 0.07	4.99 ± 0.13	78.6 ± 0.4		
		Solvolysis (obsd)	0.98 ± 0.04	7.09 ± 0.09	3.73 ± 0.07	88.2 ± 0.5	11.0 ± 0.5	1.90 ± 0.06
	0.66	$NaOCH_3$ only (calcd)	8.97 ± 0.25	10.15 ± 0.30	5.40 ± 0.21	75.5 ± 2.4	1.74 ± 0.07	1.88 ± 0.07

[a] Full data are presented for the solvolysis runs, but only a selection of data for $NaOCH_3$ runs. Full data for the latter are listed in the dissertation of Bartsch.[1]

methoxide. Table III is again but a selection of the data actually obtained.[40]

From similar though less complete studies, other workers have reported only the proportion of each olefin in the mixture of isomeric olefins obtained. To facilitate comparison with other work, as well as comparison among our own results at a common temperature, we list in Table IV the olefin distributions from the present study, extrapolated to a common temperature of 100°.

In Table IV, it is plain that both the 2-hexenes:1-hexene ratio and 2-hexene *trans*:*cis* ratio increase regularly among the halides in the order F < Cl < Br < I. However, 2-hexyl brosylate does not conform to the qualitative correlation that exists among the halides; thus it lies between chlorine and fluorine in respect to its 2-hexenes:1-hexene ratio, but beneath fluorine in its *trans*:*cis* ratio.

2-Fluorohexane gives predominantly Hofmann orientation, in agreement with the experience of Saunders, *et al.*,[5] with sodium ethoxide induced elimination from 2-pentyl fluoride. In further agreement with them, 2-fluorohexane gives a low *trans*:*cis* ratio.

In Table III, the very high proportion of 2-hexenes in solvolytic elimination from 2-hexyl brosylate is remarkable. Strong Saytzeff orientation in E1 reactions was noted years ago by Hughes and Ingold.[41]

Table IV. Olefin Compositions Obtained from Reactions with $NaOCH_3$, Extrapolated to 100°[a]

Leaving group	1-Hexene, %	*trans*-2-Hexene, %	*cis*-2-Hexene, %	**2:1**	*trans*:*cis*
F	69.9	21.0	9.1	0.43	2.3
Cl	33.3	49.5	17.1	2.0	2.9
Br	27.6	54.5	17.9	2.6	3.0
I	19.3	63.0	17.6	4.2	3.6
$OSO_2C_6H_4Br$-*p*[b]	41.7	36.3	22.0	1.4	1.7

[a] All values ±0.5%. [b] Corrected for competing methanolysis.

It is also remarkable that the *trans*:*cis* ratio from the E1 reaction is nearly the same as from the E2 reaction of the brosylate with sodium methoxide. Inasmuch as the transition states of the two reactions (the E2 and the second step of the E1) are quite different, it is not unreasonable that the two kinds of product ratio are not correlated.

In Tables II and III, the yield of the substitution product is low with 2-hexyl iodide (about 16%), modest with the bromide, chloride, and fluoride (25–35%), and high with the brosylate (75–80% in the $NaOCH_3$ reactions). The proportion of substitution decreases

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(41) M. L. Dhar, E. D. Hughes, and C. K. Ingold, *J. Chem. Soc.*, 2065 (1948).

with temperature for all substrates except the iodide, for which it is nearly invariant with temperature. Within the temperature ranges investigated, the per cent 2-hexyl methyl ether formed was empirically linear with temperature, as demonstrated in Figure 1 for two substrates. Such plots were useful to us for interpolation purposes.

Kinetics. Determination of the rate of solvolysis of 2-hexyl brosylate was carried out in the presence of 2,6-lutidine, whose purpose was to neutralize the *p*-bromobenzenesulfonic acid formed in the reaction. Each run gave good first-order kinetics. The rate coefficients obtained are set forth in Table V. These data give a linear Arrhenius plot. Inasmuch as the concentrations of both substrate and lutidine at 50.8° were about double what they were at other temperatures, this confirms that the reaction is first order in substrate and shows that it is zero order in lutidine. For methanolysis of 2-hexyl brosylate, $\Delta H^{\ddagger}$ is 23.2 ± 2.3 kcal/mole and $\Delta S^{\ddagger}$ is -4.7 ± 6.9 cal deg^{-1} mole^{-1}. These parameters are computed from the over-all first-order rate coefficients, and may be composite.

Table V. First-Order Rate Coefficients for the Methanolysis of 2-Hexyl *p*-Bromobenzenesulfonate

Temp, °C	Substrate, *M*	2,6-Lutidine, *M*	$k_1 \times 10^5$, sec^{-1}
44.3	0.0629	0.103	5.96 ± 0.21
50.8	0.115	0.266	12.1 ± 0.3
59.8	0.0629	0.103	35.2 ± 1.8

In the reactions with sodium methoxide, the base was always in large excess over the substrate, and pseudo-first-order kinetics were observed. Each pseudo-first-order rate coefficient (k_ψ) was dissected, with reference to product compositions, into components relating to formation of the four products, and each of the latter was converted into a second-order rate coefficient by dividing by the sodium methoxide concentration at the temperature of the experiment. In the case of 2-hexyl brosylate,[42] the computation procedure was somewhat more complex, as explained in the Experimental Section, owing to the solvolysis complication.

The second-order rate coefficients for formation of all products from all substrates at all temperatures are displayed in Table VI.

In Table VI, attention is called to manifold evidence that all the reactions studied are second order, first order in substrate and first order in sodium methoxide. In the case of 2-hexyl fluoride, the three runs at 149.8° represent variation of both base and substrate concentrations by a factor of two. The fact that the second-order rate coefficients are but slightly changed demonstrates second-order kinetics. The small regular increase between 1.25 and 2.04 *M* $NaOCH_3$ is attributed to a small deviation of the appropriate acidity function[43] from sodium methoxide concentration. Several other verifications of second-order kinetics are contained within Table VI.

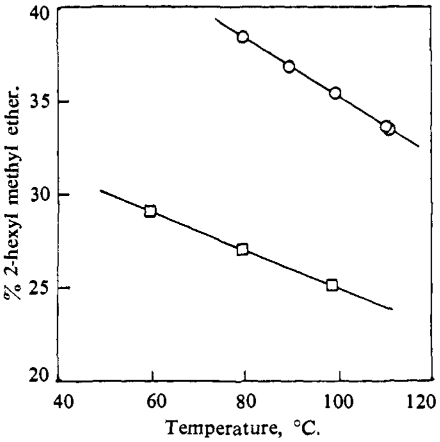

Figure 1. Yields of 2-hexyl methyl ether from 2-chlorohexane (circles) or 2-bromohexane (squares), as a function of temperature.

Second-order rate coefficients were thus available at four or five temperatures for each of the 20 bimolecular reactions studied, and each set of data covered a temperature span of at least 30°. The Arrhenius plots showed satisfactory linearity. The enthalpies and entropies of activation which were calculated are set forth in Table VII. This table also includes rate coefficients for all 20 reactions interpolated or extrapolated to 100°, both in absolute units and relative to 2-hexyl chloride within each set.

Discussion

Evidence for the E2 Mechanism. That these eliminations occur by the E2 mechanism is shown by several types of evidence. The second-order kinetics rule out the El mechanism. The fact that hydrogen isotope exchange by 2-pentyl fluoride does not accompany its elimination reaction with sodium ethoxide in ethanol-O-*d*[44] demonstrates that reaction does not occur *via* a β-carbanion in equilibrium with reactants. It is important that this demonstration concerns the leaving group most conducive to the "reversible carbanion" mechanism.[45] The fact that there is a strong element effect[46] with respect to the leaving group shows that the mechanism is not rate-limiting formation of a β-carbanion followed by rapid expulsion of the leaving group. Indeed, that mechanism would call for the fastest elimination with the most strongly electron-attracting halogen leaving group, whereas the reactions are the slowest in that case.

Linear Free Energy Relationships. Never before have accurate data been available for the rates of formation of alternative isomeric olefins from a series of 2-substituted alkanes in which the 2 substituent was widely varied. The data in Tables VI and VII therefore encourage a search for novel correlations.

In Figure 2, log k_2 for formation of *trans*-2-hexene is plotted, for each substrate, against log k_2 for formation of 1-hexene from the same substrate. All data are for 100°. Figure 3 is a similar plot in which log k_2 for *cis*-

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(42) The observed pseudo-first-order rate coefficients (k_ψ) for the total of all reactions of 2-hexyl brosylate with sodium methoxide in methanol were as follows (all in units of sec^{-1} × 10^4): 29.7°, 0.66 *M* $NaOCH_3$, 0.539 ± 0.011; 44.3°, 0.66 *M* $NaOCH_3$, 3.17 ± 0.14; 50.8°, 0.66 *M* $NaOCH_3$, 6.64 ± 0.05; 1.25 *M* $NaOCH_3$, 11.1 ± 0.6; 59.8°, 0.66 *M* $NaOCH_3$, 14.3 ± 0.4.

(43) K. Bowden, *Chem. Rev.*, **66**, 119 (1966); C. H. Rochester, *Quart. Rev.* (London), 20, 511 (1966).

(44) W. H. Saunders, Jr., and M. R. Schreiber, *Chem. Commun.*, 145 (1966).

(45) D. J. McLennan, *Quart. Rev.* (London), in press.

(46) J. F. Bunnett, E. W. Garbisch, Jr., and K. M. Pruitt, *J. Am. Chem. Soc.*, 79, 385 (1957).

Table VI. Second-Order Rate Coefficients for Formation of Various Products from the Reactions of 2-Substituted Hexanes with $NaOCH_3$ in CH_3OH

			$k_2 \times 10^5$, l. mole^{-1} sec^{-1}, for the formation of			
2-Substituent	Temp, °C	CH_3ONa,[a] M	1-Hexene	*trans*-2-Hexene	*cis*-2-Hexene	2-Hexyl methyl ether
F	129.5	2.04	0.116 ± 0.002	0.0319 ± 0.0005	0.0136 ± 0.0010	0.0627 ± 0.005
	139.6	2.04	0.303 ± 0.009	0.0813 ± 0.0021	0.0329 ± 0.0034	0.137 ± 0.003
	149.8	1.25	0.590 ± 0.025	0.171 ± 0.007	0.0743 ± 0.0074	0.335 ± 0.012
	149.8[b]	2.04	0.712 ± 0.033	0.186 ± 0.007	0.0770 ± 0.0077	0.406 ± 0.018
	149.8[c]	2.04	0.771 ± 0.035	0.199 ± 0.009	0.0890 ± 0.0065	0.441 ± 0.018
	164.4	2.04	2.55 ± 0.09	0.630 ± 0.020	0.258 ± 0.029	1.16 ± 0.04
Cl	79.8	0.660	0.448 ± 0.034	0.792 ± 0.057	0.249 ± 0.019	0.925 ± 0.066
	89.5	0.660	1.22 ± 0.01	1.97 ± 0.02	0.611 ± 0.012	2.21 ± 0.03
	98.8	0.660	3.46 ± 0.10	5.28 ± 0.11	1.66 ± 0.10	5.75 ± 0.14
	99.0	1.253	3.46 ± 0.11	5.12 ± 0.12	1.78 ± 0.06	5.24 ± 0.14
	111.7	0.660	11.6 ± 0.2	16.3 ± 0.2	5.84 ± 0.08	17.0 ± 0.3
Br	44.3	1.253	0.309 ± 0.012	0.914 ± 0.028	0.245 ± 0.008	0.638 ± 0.022
	57.9	0.638	1.55 ± 0.04	4.18 ± 0.03	1.14 ± 0.04	2.83 ± 0.04
	59.8	0.638	1.83 ± 0.05	4.87 ± 0.09	1.40 ± 0.03	3.32 ± 0.07
	59.8	1.253	2.01 ± 0.04	5.26 ± 0.13	1.48 ± 0.10	3.54 ± 0.11
	72.3	0.638	9.06 ± 0.19	21.5 ± 0.4	6.30 ± 0.21	14.3 ± 0.3
	72.3	1.253	10.0 ± 0.2	23.2 ± 0.6	6.80 ± 0.28	14.9 ± 0.6
	79.8	0.638	20.7 ± 0.8	46.9 ± 0.8	13.9 ± 0.6	30.4 ± 1.2
	79.8	1.253	18.5 ± 1.0	41.6 ± 2.3	12.1 ± 0.8	25.4 ± 1.4
I	29.7	0.638	0.214 ± 0.05	1.41 ± 0.03	0.304 ± 0.009	0.364 ± 0.018
	44.3	0.638	1.43 ± 0.03	8.07 ± 0.11	1.83 ± 0.11	2.16 ± 0.07
	59.8	1.253	10.7 ± 0.7	47.2 ± 1.8	12.3 ± 0.7	12.0 ± 0.6
	62.8	0.638	12.9 ± 0.2	59.6 ± 0.9	14.9 ± 0.9	16.6 ± 0.4
	72.3	0.638	35.3 ± 1.1	146 ± 5	38.1 ± 1.1	41.8 ± 1.4
OBs[d]	29.7	0.660	0.378 ± 0.013	0.526 ± 0.013	0.255 ± 0.008	5.65 ± 0.15
	44.3	0.660	2.88 ± 0.18	3.57 ± 0.21	1.81 ± 0.10	31.6 ± 1.9
	50.8	0.660	6.96 ± 0.13	7.92 ± 0.13	4.12 ± 0.08	67.8 ± 1.7
	50.8	1.253	6.80 ± 0.42	7.82 ± 0.48	4.23 ± 0.27	67.7 ± 3.7
	59.8	0.660	15.3 ± 0.5	17.3 ± 0.5	9.22 ± 0.35	129 ± 4

[a] Uncorrected for thermal expansion of methanol. [b] $C_6H_{13}F$, 0.0087 M. [c] $C_6H_{13}F$, 0.0155 M. [d] *p*-Bromobenzenesulfonate; the data for this substrate have been corrected for solvolysis.

Table VII. Reactions of 2-Substituted Hexanes with $NaOCH_3$ in CH_3OH. Summary of Kinetic Results

Product	2-Substituent	k_2 at 100°, l. mole^{-1} sec^{-1}	k_2, relative[a]	$\Delta H^{\ddagger}$, kcal mole^{-1}	$\Delta S^{\ddagger}$, cal deg^{-1} mole^{-1}
1-Hexene	F	5.46×10^{-8}	0.0014	30.2 ± 0.5	−13.5 ± 1.5[b]
	Cl	3.78×10^{-5}	(1.00)	27.1 ± 0.4	−9.0 ± 1.2[b]
	Br	1.44×10^{-3}	38.1	25.3 ± 0.5	−6.2 ± 1.5[b]
	I	5.68×10^{-3}	150	24.7 ± 0.5	−6.0 ± 1.5[b]
	OBs[c]	1.07×10^{-2}	283	24.4 ± 1.1	−4.7 ± 3.3[b]
trans-2-Hexene	F	1.68×10^{-8}	0.00030	29.1 ± 0.4	−16.6 ± 1.2
	Cl	5.68×10^{-5}	(1.00)	25.1 ± 0.4	−11.2 ± 1.2
	Br	2.92×10^{-3}	51.2	23.7 ± 0.5	−7.1 ± 1.5
	I	1.80×10^{-2}	317	22.1 ± 0.3	−7.8 ± 0.9
	OBs[c]	9.35×10^{-3}	165	23.0 ± 0.9	−6.6 ± 2.7
cis-2-Hexene	F	7.20×10^{-9}	0.00038	29.0 ± 0.8	−18.7 ± 2.4
	Cl	1.88×10^{-5}	(1.00)	26.2 ± 0.6	−10.6 ± 1.8
	Br	8.73×10^{-4}	46.4	24.1 ± 0.5	−8.5 ± 1.5
	I	5.32×10^{-3}	283	23.1 ± 0.4	−7.5 ± 1.2
	OBs[c]	5.48×10^{-3}	291	23.6 ± 0.9	−6.2 ± 2.7
2-Hexyl methyl ether	F	3.13×10^{-8}	0.00051	29.5 ± 1.7	−14.3 ± 5.1
	Cl	6.08×10^{-5}	(1.00)	24.0 ± 0.6	−13.8 ± 1.8
	Br	1.93×10^{-3}	31.7	23.4 ± 0.5	−8.7 ± 1.5
	I	5.22×10^{-3}	85.9	22.5 ± 0.1	−9.3 ± 0.3
	OBs[c]	4.63×10^{-2}	762	20.5 ± 0.9	−10.2 ± 2.7

[a] Relative to 1.00 for 2-hexyl chloride within each set. [b] All $\Delta S^{\ddagger}$ for 1-hexene formation are calculated from statistically corrected rate coefficients. [c] *p*-Bromobenzenesulfonate.

2-hexene formation is plotted against log k_2 for 1-hexene formation.

In both plots, the points for the four 2-hexyl halides define a straight line to which that for 2-hexyl brosylate does not conform.[47] This attests to regularities in the leaving group effect on product composition among the halide reactions, which do not extend to the brosylate ester. The implications of these plots are discussed below.

The slopes in Figures 2 and 3, based on the 2-hexyl halide points only, are 1.19 and 1.16, respectively. Thus, the rate of *cis*-2-hexene formation increases 14% faster than that of 1-hexene as the leaving group improves, and *trans*-2-hexene formation is accelerated yet another 1%.

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(47) The standard deviation of the halogen points from the line they define is 0.071 and 0.075 in the *cis* and *trans* plots, respectively, corresponding to standard deviations of individual rate coefficients from the linear regression lines of 18 and 19%.

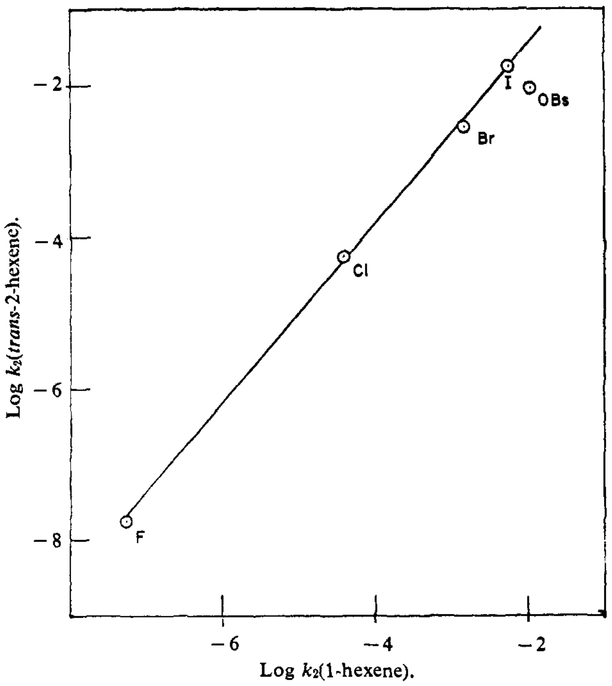


Figure 2. Linear free energy relationship between logarithms of rates of *trans*-2-hexene and 1-hexene formation.

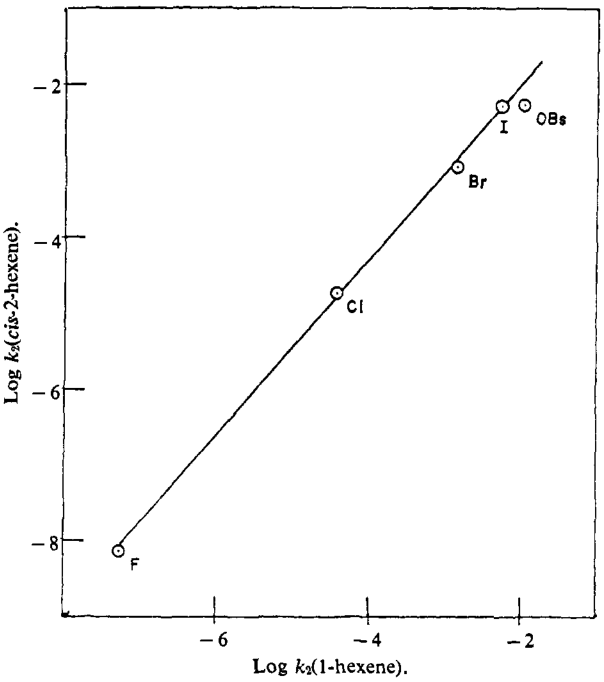


Figure 3. Linear free energy relationship between logarithms of rates of *cis*-2-hexene and 1-hexene formation.

Hofmann Orientation from 2-Hexyl Fluoride. The report that 2-fluoropentane with sodium ethoxide gives more 1-pentene than 2-pentenes[5] would seem to have vitiated the hypothesis that Hofmann orientation is always due to a large steric requirement of the leaving group. However, Brown and Klimisch[7] hesitated to forsake that hypothesis because olefins had been obtained only in small yields from 2-pentyl fluoride, accompanied by unspecific amounts of other products, and because the kinetics and mechanism of elimination from alkyl fluorides were incompletely established. They also speculated that the incipient fluoride ion might require more solvation in the E2 transition state than other halide ions, with consequent increase in the steric requirements of the solvated leaving group.

The uncertainties which underlay those reservations are now dispelled. As in the 2-fluoropentane–ethoxide reaction, 2-fluorohexane with sodium methoxide gives mainly the terminal olefin. Now all the products of the reaction are accounted for, and the reaction is shown to be kinetically first order in each reactant.[48] The possibility of the carbanion mechanism of elimination is denied by experimental evidence, as discussed above. Moreover, base-promoted elimination of the elements of HF from cycloalkyl fluorides resembles other E2 reactions in its stereochemical requirements.[49] The evidence indicates that base-induced eliminations from *sec*-alkyl fluorides have the same kinetics and mechanism as more familiar E2 reactions.

As to solvation of the fluoride leaving group, increased solvation of the transition state should depress the entropy of activation. Our data (Table VII) show that each E2 reaction, for formation of a particular olefin, has essentially the same $\Delta S^{\ddagger}$ for 2-hexyl iodide and bromide, a somewhat lower $\Delta S^{\ddagger}$ for the chloride, and a still lower one for the fluoride. This constitutes evidence for some additional solvation of the chloride and even more of the fluoride transition states.

Recent work of Illuminati and coworkers[50] indicates that incorporation of one methanol molecule of solvation into a transition state lowers $\Delta S^{\ddagger}$ by about 8 eu. Also relevant is the entropy of fusion of methanol (4.4 eu).[51] Inasmuch as $\Delta S^{\ddagger}$ is from 7 to 11 eu lower for the fluoride than for the iodide reactions, solvation of the 2-hexyl fluoride E2 transition state exceeds that of the iodide by an average of one or two methanol molecules.

Almost certainly the extra methanol molecule(s) of solvation is associated by hydrogen bonding with fluorine, in the sense $F\cdots H—OCH_3$. The F—O distance is probably about 2.5 A,[52] and the $C\cdots F\cdots O$ angle about 109°. It is evident from Courtauld atomic models that the solvating methanol molecule(s) does not contact the β-propyl group in any of the 2-hexene-forming E2 transition states providing that the propyl group and the methyl group of the methanol are rotated into favorable conformations. Some loss of rotational entropy would be caused by the exclusion of certain conformations, and some of the reduced $\Delta S^{\ddagger}$ of the 2-hexyl fluoride reactions may be of this origin, but solvation of fluorine does not increase its steric requirements[7] in the transition state.[53]

(48) This agrees with earlier evidence of second-order kinetics in the reaction of "*sec*-amyl fluoride" (probably a mixture of 2- and 3-fluoropentanes) with sodium ethoxide: N. B. Chapman and J. L. Levy, *J. Chem. Soc.*, 1673 (1952).

(49) J. Burdon, T. M. Hodgins, R. Stephens, and J. C. Tatlow, *ibid.*, 2382 (1965).

(50) M. Calligaria, G. Illuminati, and G. Marino, *J. Am. Chem. Soc.*, **89**, 3518 (1967).

(51) A. R. Ubbelohde, *Quart. Rev.* (London), **4**, 356 (1950).

(52) J. A. A. Ketelaar, "Chemical Constitution," Elsevier Publishing Co., Amsterdam, Netherlands, 1958, p 416.

(53) The proposal of Brown and Klimisch[7] that the axial–equatorial equilibrium of cyclohexane derivatives be used as a model to estimate the steric requirements of leaving groups in E2 transition states is of dubious value. The conformational free energy difference, $\Delta G_X{}^{\circ}$, changes very little among the cyclohexyl halides[54] despite obvious differences in the distances of closest approach of axial halogens and

The linear relationships of Figures 2 and 3 also testify that the trend toward more Hofmann elimination with decreasing atomic number of the halogen is not an expression of steric effects. Consider the reactions producing 1-hexene and *trans*-2-hexene. The change in product ratio reports that, at 100°, the $\Delta\Delta G^{\ddagger}$ for formation of *trans*-2-hexene as compared to 1-hexene is −860 cal for the iodide and +890 cal for the fluoride. All free energies of activation are higher for the fluoride than the iodide, but $\Delta G^{\ddagger}$ for *trans*-2-hexene formation increases 1.75 kcal more than that for 1-hexene formation. This is the increment of $\Delta G^{\ddagger}$ which any theory of orientation must account for.

The linear plot of Figure 2 shows that the special increment of $\Delta G^{\ddagger}$ for *trans*-2-hexene formation is imposed, halogen by halogen, in linear proportion to the increase in $\Delta G^{\ddagger}$ for the 1-hexene reaction. The general increase in $\Delta G^{\ddagger}$ is not of steric origin; it has to do with the energy required to break C–X bonds, the decrease in transition-state entropy owing to incorporation of an additional methanol molecule(s) of solvation,[56] and related electronic readjustments. It would be an extraordinary coincidence if steric and nonsteric increments of $\Delta G^{\ddagger}$ were imposed in constant proportion through two series of four reactions each.

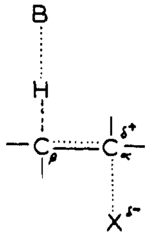
In summary, the hypothesis that changes in positional orientation among the 2-hexyl halide eliminations stem from crowding between leaving groups and β-alkyl groups is at variance with the actual steric requirements of the halogen leaving groups and it is contradicted by the linear free energy plots of Figures 2 and 3. Insofar as the halogen leaving groups are concerned, the hypothesis is dismissed. However, when very large β substituents and leaving groups are involved, this hypothesis has obvious relevance. To establish the point at which steric compression effects become predominant is a worthy objective for future research.

The hypothesis that Hofmann orientation obtains only when the acidity of β-hydrogens is increased to a certain level by the polarity of leaving groups is also inadequate to explain the trends we have observed. The Taft σ^* values of XCH_2 groups are: ICH_2, 0.85; $BrCH_2$, 1.00; $ClCH_2$, 1.05; FCH_2, 1.10; p-$CH_3C_6H_4$-SO_2OCH_2, 1.31.[57,58] The polar effect of fluorine is not enough different from that of the other halogens to account for the change from Saytzeff to Hofmann orientation between the chloride and fluoride, and the leaving group with the greatest electron-attracting effect (*p*-bromobenzenesulfonoxy) does not give the highest proportion of 1-hexene.

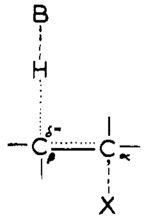
Though the polarity of the leaving group, by itself, does not control orientation among the reactions we have studied, it probably does affect the over-all character of the transition state, and thus contributes in a subsidiary way.

Orientation and the Theory of the Variable E2 Transition State. This theory[9] gives a good account of both the positional and geometrical orientations observed.

In an E2 reaction, bonds are formed between the base and H_β and between C_β and C_α, and the H–C_β and C_α–X bonds are broken. The reaction is concerted; all bond making and bond breaking occurs in one step, but the several bonds are not necessarily formed and ruptured synchronously. Thus, C_α–X breaking may be farther advanced than C_β–H breaking at the transition state, causing it to have partial C_α carbonium ion character. The extreme of such a transition state resembles that for the first step of E1 elimination. It is called the "nearly E1" extreme, and is represented by structure **1**.



1
"nearly E1"



2
"nearly carbanion"

The opposite extreme, in which C_β–H rupture is far advanced over C_α–X breaking, has partial C_β carbanion character; the "nearly carbanion" extreme is represented by structure **2**. Between these extremes, there is a continuum of transition states of varying character. In the middle lie "central" transition states, in which the degrees of C_β–H and C_α–X breaking are equal and a large degree of C=C character is developed.

The character of a particular transition state is determined by the interplay of a number of influences such as how "good" the leaving group is, what the solvent is, what α and β substituents are present, and how strong the base is. The way in which most of these affect the character of the transition state has been discussed by Bunnett.[9] The effect of base strength was discussed in the pioneering paper of Cram, *et al.*,[59] and cogent experimental evidence has recently been provided by Froemsdorf and Robbins.[60]

The character of a transition state has certain experimentally tangible consequences. For example, the degree of double bond character in the C_β–C_α bond is relatively small at either extreme of the continuum of transition states, but relatively large in the middle. Thus eclipsing between alkyl groups destined for a *cis* relationship, which tends to retard formation of the *cis* olefin, is relatively great in "central" transition states. As the character of the transition state shifts from "central" toward either extreme, a decrease in the *trans*:*cis* ratio should occur.

The character of the transition state also determines the kinetic effect of a β-alkyl substituent, that is, whether Hofmann or Saytzeff orientation will prevail. A β-alkyl group lowers the energy of "central" or "nearly E1" transition states by electron release to the developing double bond or through it to a C_α with partial carbonium ion character, but somewhere between "central" and the "nearly carbanion" extreme the degree

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nearby axial hydrogens. Moreover, it is possible that the differences in $\Delta G_X{}^\circ$ are not primarily of steric origin.[55]

(54) E. L. Eliel, *Angew. Chem. Intern. Ed. Engl.*, **4**, 761 (1965).

(55) M. Charton and B. I. Charton, *J. Chem. Soc., Sect. B*, 43 (1967).

(56) The decrease in $\Delta S^{\ddagger}$ is approximately linear with the increase in $\Delta H^{\ddagger}$ for all three elimination reactions, but not for the substitution. Viewed as isokinetic plots, these would have isokinetic temperatures below absolute zero!

(57) R. W. Taft, Jr., in "Steric Effects in Organic Chemistry," M. S. Newman, Ed., John Wiley and Sons, Inc., New York, N. Y., 1956, p 619.

(58) J. Hine and O. B. Ramsay, *J. Am. Chem. Soc.*, **84**, 973 (1962).

(59) D. J. Cram, F. D. Greene, and C. H. DePuy, *ibid.*, **78**, 790 (1956).

(60) D. H. Froemsdorf and D. M. Robbins, *ibid.*, **89**, 1737 (1967).

of double bond character has sufficiently diminished and the degree of β-carbanion character sufficiently increased so that a β-alkyl group is no longer helpful. To the "nearly carbanion" side of that point, the unfavorable interaction of a β-alkyl group with negative charge on C_β predominates, and Hofmann orientation prevails.[9]

Changing the leaving group through the series of halogens from iodine to fluorine alters the character of the transition state. First and foremost, the change to a poorer leaving group obliges the system to strike a different balance between C–H and C–X bond breaking at the transition state in order to attain the optimum energetic pathway between reactants and products. As the C–X bond becomes harder to break, the degree of C–X breaking decreases and that of C_β–H rupture augments. This shift toward the "nearly carbanion" extreme is reinforced by the fact that the lighter halogens are more strongly electron attracting; even though partly detached at the transition state, they assist the development of β-carbanion character.

Though it is as yet not possible to specify the exact position of a particular transition state in the continuum, or to quantify the shift which occurs on a given change of leaving group, the theory does raise the expectation that a change in leaving group from iodine through bromine and chlorine to fluorine should cause a steady increase in the proportion of Hofmann product and in the appropriate system an inversion from mainly Saytzeff to mainly Hofmann orientation. These are the very effects which we have observed, as evident in Table IV.

As to geometrical orientation, it is expected from the theory that if the transition state for the iodo substrate is "central" or somewhat off toward the "nearly carbanion" side, the degree of eclipsing of groups destined for a *cis* relationship will decrease as the halogen leaving group is changed toward fluorine, with consequent decrease in the *trans*:*cis* ratio. This expectation is also fulfilled by our observations (Table IV).

Neither the reasonableness of the theory of the variable E2 transition state nor its success in rationalizing a couple of sets of data proves that it is correct. However, the fact that this theory gives a good account of a variety of observations,[5,7,9,60,61] including some of types not anticipated when the theory was given its first full formulation,[9] shows that it has general utility and suggests that it is right.

Entropy Effects Favoring 1-Hexene Formation. Elimination from any of the five substrates to form 1-hexene is statistically favored over elimination to *cis*- or *trans*-2-hexene by a factor of three, equivalent to a difference in $\Delta S^{\ddagger}$ of 2.2 eu. The $\Delta S^{\ddagger}$ values for 1-hexene in Table VII are, however, based on statistically corrected rate coefficients.

Even after the statistical correction has been applied, the $\Delta S^{\ddagger}$ for 1-hexene generation from any substrate is lower than for either 2-hexene by about 2 eu. In part, the transition states may anticipate the entropy differences between the olefins formed; the entropies of the 2-pentenes and the 2-heptenes are lower than of the corresponding 1-alkenes by 1–2 eu at 400–600°K.[62]

It is also possible that the conformational freedom of the methoxide and alkyl moieties is less in the transition states leading to the 2-hexenes. Strainfree conformations are available to all transition states but, as a consequence of the proximity of the methoxide and alkyl moieties in the transition states leading to the 2-hexenes, some conformations must be avoided to escape steric strain. Restriction of conformational freedom depresses the entropy of a transition state.

Orientation from 2-Hexyl Brosylate. In Figures 2 and 3, the brosylate data do not conform to the linear relationships which obtain for reactions of the 2-hexyl halides. The rates of formation of both *trans*- and *cis*-2-hexene are lower than one would expect from the rate of formation of 1-hexene and the correlation which exists among the halogen points. The deviations are -0.62 and -0.28 log unit in the *trans*- and *cis*-2-hexene rates, respectively, corresponding to rate depressions of 4.2- and 1.9-fold. The deviations are at least four times the standard deviations of the halogen points from the line they define.

These deviations suggest that even in methanol solvent some factor operates to depress the *trans*:*cis* ratio, though not enough to cause the *cis* isomer to predominate as it does in *t*-butyl alcohol.[16,60] However, the factor need not be the same which is principally responsible for the predominance of the *cis* isomer in *t*-butyl alcohol.

It is conceivable that these effects are entropic in origin, reflecting the varying amounts of rotational freedom in the three alternative transition states.[17] Examination of Courtauld atomic models indicates that the conformational freedom of the limber brosylate group, concerning rotation about C–S, S–O, and O–C bonds, is less in the transition state preceding *cis*-2-hexene than in that for 1-hexene, and still less in that for *trans*-2-hexene. The principal difference among these transition states is in the amount of obstruction offered by C_4 and its associated hydrogens. The observed deviations are of a magnitude reasonably attributable to rotational entropy effects, but it is noted in Table VII that the differences in $\Delta S^{\ddagger}$ between the reactions affording 1-hexene and those giving the 2-hexenes are no greater for the brosylate than for the halides. On the other hand, the decrements in $\Delta S^{\ddagger}$ which would account for the observed rate effects (1.3 or 2.9 eu) are less than the standard deviations of the experimental entropies of activation. Thus, the available experimental evidence neither supports nor denies an entropic interpretation.

Examination of models indicates that conformations are available to all transition states in which direct compression of C_4 and its hydrogens against the brosylate group can be avoided. Thus orientation does not appear to be governed by enthalpic effects of steric origin.

Acknowledgments. We thank Professor Harold R. Ward for advice on problems of gas–liquid partition chromatography. The hospitality of the Department of Chemistry, University of Canterbury, Christchurch, New Zealand, in which this manuscript was composed, is deeply appreciated.

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[61] L. J. Steffa and E. R. Thornton, *J. Am. Chem. Soc.*, **85**, 2680 (1963); W. H. Saunders, Jr., and S. E. Zimmerman, *ibid.*, **86**, 3789 (1964); W. H. Saunders, Jr., A. F. Cockrill, S. Asperger, L. Klasinc, and D. Stefanovic, *ibid.*, **88**, 848 (1966); G. Ayrey, A. N. Bourns, and V. A. Vyas, *Can. J. Chem.*, **41**, 1759 (1963); J. F. Bunnett and E. Baciocchi, *J. Org. Chem.*, **32**, 11 (1967); D. J. McLennan, *J. Chem. Soc., Sect B*, 705, 709 (1966).

[62] K. W. Egger and S. W. Benson, *J. Am. Chem. Soc.*, **88**, 236 (1966); K. W. Egger, *ibid.*, **89**, 504 (1967).