Steric Effects in Elimination Reactions. I. Directive Effects in Unimolecular Eliminations; A Case of Hofmann Rule Elimination in an E1 Reaction

By Herbert C. Brown and Ichiro Moritani[1]

Rate data and olefin formation for a number of tertiary alkyl halides have been studied in 85% aqueous n-butyl Cellosolve. The use of this solvent, in the presence of triethanolamine to neutralize the acid formed in the hydrolysis, offers many advantages for the quantitative recovery and identification of the olefins formed in the solvolysis. The solvolyses of t-amyl bromide, dimethylisopropylcarbinyl bromide, and diethylmethylcarbinyl bromide all proceed in accordance with the Saytzeff rule. However, the solvolyses of dimethylneopentylcarbinyl chloride, bromide and iodide proceed to give 81% of 2,4,4-trimethyl-1-pentene and 19% of 2,4,4-trimethyl-2-pentene, obviously a case of elimination in accordance with the Hofmann rule. The identical results obtained with the chloride, bromide and iodide support the conclusion that the elimination must be proceeding through a carbonium ion intermediate. It is proposed that steric effects are responsible for this change in the direction of unimolecular elimination from the usual Saytzeff to Hofmann type.

Directive effects in unimolecular elimination reactions have been discussed previously by Hughes, Ingold and their co-workers.[2,3] They conclude that unimolecular eliminations proceed to give the most branched olefin. Such eliminations are considered to follow the Saytzeff rule of orientation. Bimolecular eliminations of 'onium salts yield the least branched olefins. Eliminations of this kind follow the alternative Hofmann rule of orientation.

They have proposed that the Saytzeff rule represents control by the electromeric factor, whereas the Hofmann rule represents control by the polar factor rendered important by the positive charge in the 'onium ion.

This problem has been under investigation in our laboratories for some time. The present group of papers reports the results of our studies on the role of the steric factor in both unimolecular and bimolecular eliminations. As a result of these studies it is our conclusion that the Saytzeff rule does indeed represent control by the electromeric factor, as proposed by Hughes and Ingold, whereas the Hofmann rule, in contradiction to their view represents control by the steric factor.

Some indication that steric effects could result in unimolecular eliminations in accordance with the Hofmann rule was obtained in a previous study.[4] It there was observed that the olefin obtained by heating dimethylneopentylcarbinyl chloride with water was predominantly 2,4,4-trimethyl-1-pentene, evidently elimination in accordance with the Hofmann rule.

Unfortunately, the experiments as they had been performed were not entirely satisfactory for the observation of the elimination reaction. The tertiary halide and the water formed separate phases. Moreover, the olefin recovered constituted only a minor fraction of the product. It therefore appeared desirable to develop more suitable experimental conditions for the elimination reaction and improved procedures for the isolation and identification of the olefin, and to utilize these conditions and procedures for a careful study of the elimination reactions of the dimethylneopentylcarbinyl

halides, along with several related tertiary halides of interest.

Results

Our original experiments utilized 80% aqueous ethanol as the solvolytic medium. However, solvolysis of tertiary halides in this medium results in the formation of the t-alkyl alcohol, t-alkylethyl ether, as well as the desired olefin. Recovery of the volatile olefins from the reaction mixtures, followed by careful purification, invariably resulted in considerable losses.

These difficulties were avoided by the use of 85% n-butyl Cellosolve (85 volumes of solvent mixed with 15 volumes of water). Unfortunately, the presence of such alkaline materials as sodium bicarbonate, calcium carbonate and sodium acetate caused separation into two layers as the reaction proceeded. However, triethanolamine served satisfactorily for the neutralization of the acid without causing this difficulty. Fortunately, experimental results in 80% ethanol and 85% n-butyl Cellosolve indicated that within experimental error the results with regard to the extent and direction of olefin formation in both solvents were identical.

A number of experiments were carried out in which synthetic mixtures of olefins were added to the solvent, along with additional materials which would be possible components of the reaction mixture. Simple distillation through a micro-fractionating column proved quite suitable to permit recoveries of 92–94% of the olefins introduced with analysis by refractive index reproducing the original composition by ±1–2%. It was concluded that the triethanolamine fully protected the olefin from possible isomerization. Some typical results of such experiments for mixtures of 2,4,4-trimethyl-1- and -2-pentene are summarized in Table I. Similar results were realized in related experiments testing the recovery of synthetic mixtures of the isomeric 2-methylbutenes and of the isomeric 2,3-dimethylbutenes.

Rates of hydrolysis of the tertiary halides utilized were determined, primarily to provide information as to the reaction time necessary to permit essentially complete solvolysis. The rate constants are summarized in Table II.

For the most part refractive indices were relied upon for analysis of the isomeric olefins produced in the solvolyses. Occasional reaction products

(1) Post-doctorate assistant at Purdue University, 1951–1953, on a contract supported by the Office of Naval Research for the study of "Steric Strains in Chemical Reactions."

(2) E. D. Hughes, C. K. Ingold, et al., J. Chem. Soc., 2093 (1948).

(3) E. D. Hughes, C. K. Ingold and V. J. Shiner, Jr., ibid., 3827 (1953).

(4) H. C. Brown and H. L. Berneis, This Journal, 75, 10 (1953).

TABLE I

RECOVERY OF THE 2,4,4-TRIMETHYLPENTENES FROM 85% n-BUTYL CELLOSOLVE

Reaction mixture	1-, %	Olefin added 2-, %	g.	n²⁰ᴅ	Olefin recovered g.	n²⁰ᴅ	Yield, %
85% n-Bu Cellosolve, 100 ml.	0	100	5.08	1.4159	4.96	1.4158	97
Triethanolamine, 6.00 g., concd. HCl, 2.00 g.							
85% n-Bu Cellosolve, 100 ml.	71	29	4.80	1.4108	4.42	1.4107	92
Triethanolamine, 8.00 g., concd. HCl, 2.60 g.							
85% n-Bu Cellosolve, 150 ml.	36.5	63.5	7.41	1.4133	6.79	1.4132	92
Triethanolamine, 10.00 g., concd. HCl, 3.30 g., 2,4,4-tri-Me-2-pentanol, 2.5 g.							
85% n-Bu Cellosolve, 150 ml.	36.5	63.5	7.50	1.4133	7.10	1.4133	94
Triethanolamine, 10.00 g., concd. HCl, 3.30 g., 2,4,4-tri-Me-2-pentanol, 2.5 g., water, 15 ml.							

TABLE II

FIRST-ORDER RATE CONSTANTS FOR THE SOLVOLYSIS OF SOME t-ALKYL HALIDES IN 85% n-BUTYL CELLOSOLVE AT 25°

Tertiary halide	k_1, hr.⁻¹
t-Amyl chloride	0.0103
t-Amyl bromide	.385
Dimethylisopropylcarbinyl bromide	.197
Diethylmethylcarbinyl bromide	.410
Dimethylneopentylcarbinyl chloride	.0751
Dimethylneopentylcarbinyl bromide	4.70

were checked by infrared analyses. In general, the agreement in results obtained by the two analytical procedures was excellent.

The solvolysis of t-amyl bromide in the 85% n-butyl Cellosolve resulted in the formation of 20% 2-methyl-1-butene and 80% of 2-methyl-2-butene. This distribution agrees well with the values of 18.3 and 81.7% for the two olefins which are reported for the solvolysis in ethanol.[5]

In the case of dimethylisopropylcarbinyl bromide there is obtained 18% of the 1- and 82% of the 2-olefin. Similarly, the case of diethylmethylcarbinyl bromide there is a marked tendency for the elimination of one of the secondary hydrogens, rather than the primary. The product shows the presence of but 3.5% of the 1-olefin.

However, in the case of the dimethylneopentylcarbinyl halides the opposite is observed—a marked preference for the elimination of the primary, rather than the secondary. Moreover, identical results are obtained for the chloride, bromide and iodide. The data are summarized in Table III.

The yields of olefin recovered from the reaction mixtures are in excellent agreement with those previously observed by bromometric analysis.[6] Indeed, if the yields are corrected for an average 92% recovery, indicated by typical blank recovery experiments, such as those reported in Table I, the agreement with the bromometric results falls well within the precision previously claimed for these data. The agreement realized in these two different methods lends confidence in the results previously obtained by utilization of a bromometric analytical procedure.[7]

(5) M. L. Dhar, E. D. Hughes and C. K. Ingold, J. Chem. Soc., 2065 (1948). It should be pointed out that recalculation of the olefin composition from the reported refractive index, n²⁰ᴅ 1.38591, utilizing the recommended A.P.I. values for 2-methyl-1- and 2-methyl-2-butene, results in a change in the composition to 11.5 and 88.5%, respectively.

(6) H. C. Brown and R. S. Fletcher, THIS JOURNAL, 72, 1223 (1950).

(7) E. D. Hughes, C. K. Ingold and V. J. Shiner, Jr., ref. 3, state that they "found the work of Brown and Fletcher [ref. 6] difficult to

Discussion

The experimental results leave no doubt that in the solvolysis of t-amyl, dimethylisopropylcarbinyl and diethylmethylcarbinyl bromides, the least branched (the 1-olefin) is formed in minor amounts. Therefore, the solvolyses of these halides proceed in accordance with the Saytzeff rule.

On the other hand, there is also no doubt that the solvolyses of the dimethylneopentylcarbinyl halides, under conditions where isomerization cannot occur, yield the least branched olefin (the 1-olefin) as the major product. The rates of solvolysis of these halides are not affected by the presence of hydroxide ion. Moreover, identical olefin compositions are obtained from the three halogen derivatives (Table III). These results leave no doubt that these are clean-cut carbonium ion reactions with no significant incursion of any bimolecular elimination reaction. Yet the results definitely correspond to elimination in accordance with the Hofmann rule.

It is believed that the Hofmann-type elimination arises from a steric effect.[4] Elimination to yield the 2-olefin would place a methyl and a t-butyl group in the cis-position. The resulting strain is sufficient, according to this interpretation, to overcome the greater electromeric stabilization of the 2-olefin in favor of the 1-derivative.
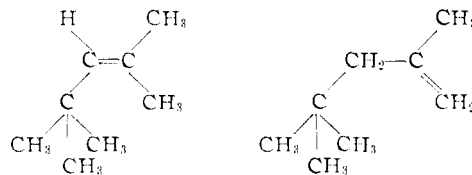
This interpretation has been criticized by Hughes, Ingold and Shiner[3] and an alternative explanation suggested. Since this alternative explanation is directly pertinent to the subject matter of a subsequent paper,[8] discussion will be deferred until after those results have been presented.

The high yield of olefin obtained in the solvolysis of dimethylneopentylcarbinyl chloride (as well as other highly branched tertiary carbonium ions) previously was attributed to the operation of steric effects in the carbonium ions in hindering the substitution and in facilitating the elimination reac-

reproduce closely, because the excesses of bromine used are not given, though they are stated to be important." Our failure to report these data arose primarily from the necessity of conforming to This Journal's standards of brevity in reporting experimental data and details.

(8) Herbert C. Brown and M. Nakagawa, THIS JOURNAL, 77, 3614 (1955).

TABLE III

EXTENT AND DIRECTION OF OLEFIN FORMATION IN THE SOLVOLYSIS OF SOME SECONDARY AND TERTIARY ALKYL DERIVATIVES

Compound	Olefin yield Isolated	Calcd.[a]	Bromo-metric[b]		Olefin composition, %
2-Butyl tosylate[c]				10.3	1-Butene[g]
				43.2	cis-2-Butene
				46.5	trans-2-Butene
2-Pentyl tosylate[c]	25			16	1-Pentene[g]
				35	cis-2-Pentene
				49	trans-2-Pentene
t-Amyl bromide[d]	30.8	34	34	20	2-Methyl-1-butene[f,g]
				80	2-Methyl-2-butene
Dimethylisopropylcarbinyl bromide[d]	58.9	64	62	18	2,3-Dimethyl-1-butene[f]
				82	2,3-Dimethyl-2-butene
Diethylmethylcarbinyl bromide[d]	40.5	44	41	3.5	2-Ethyl-1-butene[g]
				38.5	cis-3-Methyl-2-pentene
				58.0	trans-3-Methyl-2-pentene
Dimethylneopentylcarbinyl chloride[d,i]	60.5	66	65	81	2,4,4-Trimethyl-1-pentene[f]
				19	2,4,4-Trimethyl-2-pentene
bromide[d]	60.4	66	65	82	1-[f,g]
				18	2-
iodide[d,h]	56.3	61	65	81	1-[f]
				19	2-
bromide[e]				80	1-[f]
				20	2-

[a] Olefin isolated corrected for an estimated 92% average recovery. [b] Olefin yields for the solvolysis of the corresponding chlorides in 80% aqueous ethanol (ref. 6). [c] Anhydrous acetic acid at 118°. [d] 85% n-butyl Cellosolve at 25°. [e] 85% n-butyl Cellosolve at 75°. [f] Analysis of olefin by refractive index. [g] Analysis of olefin by infrared. [h] Iodide purity 92.6% (see Expt. part). [i] E. D. Hughes, C. K. Ingold and V. J. Shiner, Jr. (ref. 3) recently have studied the solvolysis of dimethyl-neopentylcarbinyl chloride in 80% aqueous ethyl alcohol at 25°. Analysis of the olefin product in three runs gave 88, 95 and 88% by refractive index and 93, 91 and 93%, resp., by infrared. Our own results have been checked repeatedly by three different workers. We are unable to account for the difference in the data.

tions.[6] This view also has been criticized recently by Hughes, Ingold and Shiner,[3] and they have suggested several alternative explanations for phenomena which we have considered to result from the operation of steric strains. Since some of the results of the following papers pertain directly to the proposed explanations, it seems best here also to defer discussion of their proposals[9] until the results of these studies have been described.[8,10]

Experimental Part

Materials.—2-Butyl and 2-pentyl tosylates were prepared by Tipson's procedure.[11] The tertiary halides were prepared by passing the gaseous hydrogen halide into the corresponding alcohols at 0°.

2-Butanol and t-amyl alcohols were commercial products which were fractionated and center cuts of constant refractive index were selected for use. 2-Pentanol, dimethylisopropylcarbinol and diethylmethylcarbinol were synthesized by standard Grignard procedures. Dimethylneopentylcarbinol was synthesized by the hydrolysis of the corresponding chloride.[4]

An attempt to prepare dimethylneopentylcarbinyl bromide by adding hydrogen bromide to diisobutylene was unsuccessful. The product was not homogeneous, as indicated by refractive index measurements on successive fractions as well as by hydrolysis data. It is probable that a mixture of primary and tertiary bromides was formed in the reaction. Treatment of the alcohol with hydrogen bromide avoided the difficulty—a pure tertiary bromide was obtained.

Dimethylneopentylcarbinyl iodide could not be purified by vacuum distillation. Excess of hydrogen iodide was removed from the crude reaction product by an aspirator and the reaction mixture was washed by ice-cold sodium bisulfite solution and dried over anhydrous magnesium sulfate. The product, n^{20}D 1.4978, exhibited a purity of 92.6% of

tertiary iodide in a solvolysis determination in 50% aqueous ethanol.

The 2-pentyl tosylate was obtained in 70.4% yield. The product could not be crystallized nor distilled in ordinary equipment. It was purified by distillation in a molecular still at $<10^{-3}$ mm. The product thus obtained exhibited n^{20}D 1.5005 and analyzed satisfactorily for the 2-pentyl tosylate.

Anal. Calcd. for $C_{12}H_{18}SO_3$: C, 59.47; H, 7.48. Found: C, 59.17; H, 7.38.

Commercial n-butyl Cellosolve was fractionated carefully under reduced pressure through a modified Widmer column. The material which distilled constantly at b.p. 62.5° at 9 mm., n^{20}D 1.4174, was utilized. The 85% n-butyl Cellosolve solution (d^{25}_4 0.9219) was prepared by mixing 2550 ml. of this purified n-butyl Cellosolve with 450 ml. of distilled water.

The olefins used in developing and testing the isolation techniques were the highest grade products available from Phillips Petroleum Co. They were carefully distilled through an efficient column (70 plates) to constant refractive index. The purity of these samples was checked occasionally by infrared analysis against Bureau of Standards spectroscopic samples.

Rate Measurements.—The procedure for determining the rates of hydrolysis was quite similar to that previously described.[12] The use of the 85% n-butyl Cellosolve as solvent offered no difficulties.

Olefin Recovery.—Approximately 5 g. of olefin, carefully weighed, was placed in 100–150 ml. of 85% n-butyl Cellosolve with excess triethanolamine and sufficient hydrochloric acid to duplicate the quantity of acid formed in a typical solvolysis. The reaction mixture was distilled through a micro column until the olefin had passed into the ice-cooled receiver and water had reached the top of the column. The small droplet of water in the receiver was removed with a capillary and the olefin fraction was dried over magnesium sulfate. The dried olefin was removed, weighed and the refractive index measured. Table I re-

(9) H. C. Brown and I. Moritani, THIS JOURNAL, 77, 3623 (1955).

(10) H. C. Brown and Y. Okamoto, ibid., 77, 3619 (1955).

(11) R. S. Tipson, J. Org. Chem., 9, 235 (1944).

(12) H. C. Brown and R. S. Fletcher, THIS JOURNAL, 71, 1845 (1949).

ports some typical results on the recovery and analysis of synthetic mixtures of the diisobutylenes. Similar results were obtained in recovery experiments for other olefins.

In addition to demonstrating the absence of any isomerization during the isolation procedure, it was established that no isomerization occurred during the hydrolysis. To typical reaction mixtures containing dimethylneopentylcarbinyl chloride and the corresponding bromide were added carefully weighed amounts of 2,4,4-trimethyl-2-pentene. In the case of the chloride the product isolated contained 51.5% of the 1-olefin as compared to a value of 50.5% calculated assuming the usual product with no isomerization of the added olefin. For the bromide, there was observed 53.0%, as compared to a value of 53.4% calculated on the same basis.

No attempt was made to develop as satisfactory a quantitative procedure for the recovery of the butenes and the pentenes from the solvolysis of the tosylates in anhydrous acetic acid. However, it was demonstrated that no isomerization of the olefins occurred under the solvolysis conditions. Of 2.0 ml. of 1-pentene, n^{20}D 1.3714, added to a

TABLE IV

ELIMINATION EXPERIMENTS

Compound	Wt. of halide, g.	Reaction time, hr.[a]	Olefin g.	yield, %	n^{20}D
t-Amyl bromide	20.56	12	4.3[b]	30.8	1.3865
Dimethylisopropyl-carbonyl bromide	22.45	25	6.75	58.9	1.4083
Diethylmethylcarbinyl bromide	22.45	11	4.64	40.5	1.4026
Dimethylneopentyl-carbinyl chloride	10.00	148	4.57	60.5	1.4100
bromide	10.00	48	3.52	60.4	1.4100
iodide	10.00	1	2.63	56.3	1.4101

[a] Estimated for a minimum of 98–99% reaction. [b] Ml.; measured by volume because of the high volatility of the pentenes.

typical reaction mixture, there was recovered 1.4 ml. of olefin (70%), n^{20}D 1.3714.

Elimination Experiments for Tertiary Halides.—A typical experiment follows. In a round-bottomed flask were placed 20.6 g. (0.13 mole) of t-amyl bromide, 21.3 g. (0.14 mole) of triethanolamine and 400 cc. of 85% n-butyl Cellosolve. The reaction mixture was placed in a constant temperature bath at 25° for 60 hours, representing the time estimated from the rate data for 98% reaction. During this time large crystals of the hydrobromide of triethanolamine separated from the solution. The flask was then attached to the Todd micro column and heated. A total of 4.3 cc. of olefin distilled over (below 35°) into the ice-cooled receiver. The olefin was separated from a droplet of water, dried over anhydrous magnesium sulfate, weighed, and its refractive index measured.

Data for one experiment for each of the tertiary halides are presented in Table IV.

The following refractive indices (n^{20}D) of the pure olefins were utilized to estimate the compositions of the olefin fractions[13]: 2-methyl-1-butene, 1.3778; 2-methyl-2-butene, 1.3874; 2,3-dimethyl-1-butene, 1.3904; 2,3-dimethyl-2-butene, 1.4122; 2,4,4-trimethyl-1-pentene, 1.4086; 2,4,4-trimethyl-2-pentene, 1.4160.

Elimination Experiments for the Tosylates.—The mixture of 100 ml. of glacial acetic acid, 4.20 g. of potassium acetate and 2 ml. of acetic anhydride was heated under reflux for 3 hours. The solution was cooled to room temperature and 10.0 g. of 2-butyl tosylate was added. The solution was again heated under reflux (118°) for 3 hours and the olefin evolved was collected in a U-tube at −80°. This sample was kindly analyzed for us by Dr. E. D. Tucker and his associates of the Standard Oil Company (Indiana) utilizing infrared absorption.

The similar solvolysis of 46.2 g. (0.2 mole) of 2-pentyl tosylate in 300 ml. of anhydrous acetic acid resulted in the isolation of 3.5 g., 25%, of olefin (n^{20}D 1.3792) which was analyzed by infrared. The data on the olefin composition are reported in Table III.

(13) "Selected Values of Properties of Hydrocarbons," American Petroleum Institute Research Projects 44 and 45.

LAFAYETTE, INDIANA

Steric Effects in Elimination Reactions. II. The Effect of the Steric Requirements of Alkyl Substituents upon the Extent and Direction of Unimolecular Elimination in the Solvolysis of Tertiary Alkyl Bromides

BY HERBERT C. BROWN AND M. NAKAGAWA[1]

The solvolysis of the group of t-alkyl bromides, $RCH_2CBr(CH_3)_2$ with R = Me, Et, i-Pr, t-Bu, was studied in order to obtain information on the effect of the steric requirements of the group R on (1) the rate of solvolysis, (2) the yield of olefin in the reaction and (3) the ratio of 1- to 2-olefin in the product. The rate of solvolysis changes in a relatively minor manner from R = Me (k_1 0.387 hr.$^{-1}$) to Et (0.296) to i-Pr (0.697), but increases sharply with R = t-Bu (k_1 4.71 hr.$^{-1}$). This sharp increase is in accord with the large strain postulated for homomorphs of di-t-butylmethane. The yield of olefin also increases with the increasing steric requirements of R: Me, 27%; Et, 32.5%; i-Pr, 46%; t-Bu, 57%. Finally, the ratio of 1- to 2-olefin changes in the direction to be expected in view of the increasing strain in the 2-olefin resulting from steric interaction between the group R and CH_3: R = Me, 0.27; Et, 0.41; i-Pr, 0.70; t-Bu, 4.26. The sharp increase with R = t-Bu is attributed to the large steric requirements of t-Bu and the fact that the strain cannot be reduced by rotation of the alkyl group. It is concluded that the phenomena observed in this family of compounds are in excellent agreement with the postulated effects of steric strains on the solvolytic behavior of tertiary halides.

The solvolysis of the dimethylneopentylcarbinyl halides proceeds to give 81% of 2,4,4-trimethyl-1-pentene and 19% of the 2-isomer.[2-4] This pre-

(1) Post-doctorate assistant at Purdue University, 1953–1954, in part on a contract supported by the Office of Naval Research, and in part on a research grant supported by the National Science Foundation.

(2) H. C. Brown and H. L. Berneis, THIS JOURNAL, **75**, 10 (1953).

(3) E. D. Hughes, C. K. Ingold and V. J. Shiner, Jr., J. Chem. Soc., 3827 (1953).

(4) H. C. Brown and I. Moritani, THIS JOURNAL, **77**, 3607 (1955).

dominant formation of the 1-olefin (Hofmann-type elimination) constitutes an important exception to the proposal by Hughes, Ingold and their co-workers[5] that unimolecular eliminations should invariably proceed to give the most branched olefin (Saytzeff-type elimination). It is important that the factors which are responsible for this exception be thoroughly understood.

(5) E. D. Hughes and C. K. Ingold, et al., J. Chem. Soc., 2093 (1948).