

care was taken to employ reaction conditions which would tend to minimize its formation.

A solution of 34.0 g. (0.200 mole) of the diethyl ester of acetylenedicarboxylic acid in 100 ml. of absolute ethanol maintained under high purity nitrogen was treated with a catalytic amount (0.2 g., 0.01 mole) of sodium causing the solution to become a clear, deep red. A second solution of 24.8 g. (0.200 mole) of *p*-toluenethiol in 100 ml. of absolute ethanol was then added very slowly, over a period of three hours, with vigorous stirring. After addition was complete, the mixture was brought to reflux for 0.5 hour, and finally was allowed to cool. No crystals formed. The mixture was placed in 500 ml. of water and acidified with a small amount of concentrated HCl (2–3 ml.). A brown oil was formed which was isolated by extraction with three 100-ml. portions of ether and subsequent evaporation of the combined ether layers under reduced pressure. The oil was purified by distillation (b.p. 166–168° at 2.0 mm.); yield 53.2 g. (90.5%) of a clear yellow oil.

Anal. Calcd. for $C_{15}H_{18}O_4S$: C, 61.2; H, 6.12. Found: C, 61.08; H, 6.13.

Ester Saponification.—The product of addition of the *p*-toluenethiol reagent to diethyl acetylenedicarboxylate was saponified by dissolving in ethanolic KOH. The solution was acidified with concentrated HCl and the solid acid which precipitated was recrystallized from aqueous ethanol, m.p. 166–167°, mixture melting point with the product of addition of the *p*-toluenethiolate reagent to acetylenedicarboxylic acid, 166–166.5°.

Preparation of *p*-Tolylmercaptomaleic Anhydride.—When a sample of the dibasic acid obtained as described above was refluxed for 10 hours with acetyl chloride, the starting material could be recovered unchanged. Dehydration of this compound in moderate yield could be attained by mixing the

di-acid (3.2 g., 0.013 mole) with 5.0 g. of phosphorus pentoxide and placing the mixture in a vacuum sublimator. The mixture was heated in boiling water for one week, keeping the pressure between 1 and 10 mm. The resulting yellow needles of anhydride were obtained in 30% yield (0.9 g.), m.p. 75.5–76.5°.

Anal. Calcd. for $C_{11}H_8O_3S$: C, 60.0; H, 3.64. Found: C, 59.70; H, 3.55.

Preparation of *p*-Tolylmercaptomaleic Acid.—A sample of the anhydride obtained in the above reaction was hydrolyzed by dissolving in aqueous NaOH, followed by acidification with concentrated HCl. The white crystals of di-acid thus obtained, m.p. 158.5–159.5°, depressed the melting point of the product of addition of *p*-toluenethiolate reagent to acetylenedicarboxylic acid to 145–148°.

*Anal.*⁹ Calcd. for $C_{11}H_{10}O_4S$: C, 55.46; H, 4.20; neut. equiv., 119. Found: C, 55.11; H, 4.39; neut. equiv., 120.

A small sample of this acid (0.2 g., 0.001 mole) was placed in 15 ml. of acetyl chloride and the mixture was refluxed on a steam-cone for 15 min. At the end of this time the acetyl chloride was stripped off using a rotary film evaporator. Acetic acid formed in the reaction was evaporated under an air jet. Seeding the yellow oil remaining with a very small crystal of the anhydride produced by sublimation immediately produced an essentially quantitative yield of the anhydride, m.p. 75.5°, mixture melting point with the anhydride obtained by sublimation, 75.5°.

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LAFAYETTE, IND.

[CONTRIBUTION FROM THE CHEMICAL LABORATORIES OF PURDUE UNIVERSITY]

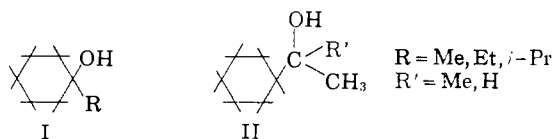
Factors Influencing the Direction of Elimination in Ester Pyrolyses

BY ROBERT A. BENKESER, JAMES J. HAZDRA AND MERWYN L. BURROUS

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A series of structurally related alcohols of the general formula $RCH_2CHOHCH_2CH_3$ were pyrolyzed *via* their xanthate (Chugaev reaction) and acetate esters. The R group was made to vary systematically from methyl to ethyl, isopropyl and *t*-butyl. In every case only two isomeric olefins were formed. The relative amount of each was determined by vapor phase chromatography. It was found that as R varied from methyl to *t*-butyl, the relative proportion of that olefin isomer which contained the double bond closest to the R group increased from 1-to-1 (methyl) to 2.3-to-1 (*t*-butyl). Thus, when R was *t*-butyl, 70% 2,2-dimethyl-3-hexene and 30% 5,5-dimethyl-2-hexene were produced. It is proposed that the direction of elimination in ester pyrolyses is influenced by the interplay of three effects: (1) statistical factors, (2) relative thermodynamic stability of the olefin products and (3) steric effects which either hinder or assist the formation of the *cis*, coplanar transition state.

Recently¹ we demonstrated that in the case of five different alcohols (structures I and II below), Chugaev elimination proceeded so as to avoid



forming a double bond *exo* to the six-membered ring.² In two of these compounds it achieved this by following the Hofmann rather than the Saytzeff rule, and in three cases it proceeded contrary to the accepted order for hydrogen removal ($3^\circ > 2^\circ > 1^\circ$).³ It was noted further that pyrolysis of the

acetate of 1-methylcyclohexanol followed a strikingly similar pattern to the Chugaev reaction, in that the ratio of 1-methylcyclohexene/methylene-cyclohexane produced was approximately 4/1 in both reactions. In this instance, at least, the acetate pyrolysis and Chugaev reaction gave very similar olefin distributions. In one sense this is a particularly satisfying observation since both reactions are thought to proceed by a similar mechanism involving a cyclic intramolecular six-membered ring transition state.⁴ On the other hand it is a result that could not be predicted *per se* since there are important differences in the two reactions.^{4a}

It has been suggested that steric considerations constitute the ultimate reason for the thermody-

(1) R. A. Benkeser and J. J. Hazdra, *THIS JOURNAL*, **81**, 228 (1959).

(2) H. C. Brown, J. H. Brewster and H. Shechter, *ibid.*, **76**, 467 (1954).

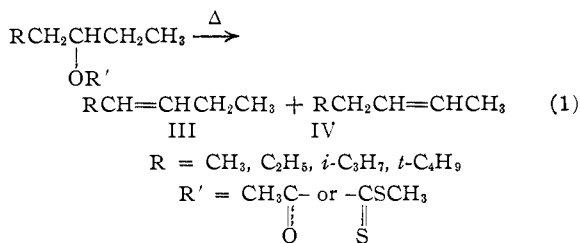
(3) J. A. Mills, *J. Chem. Soc.*, 260 (1953); see also "Steric Effects in Organic Chemistry," edited by M. S. Newman, John Wiley and Sons, Inc., New York, N. Y., 1956, p. 313.

(4) P. G. Stevens and J. H. Richmond, *THIS JOURNAL*, **63**, 3132 (1942); (b) C. D. Hurd and F. H. Blunck, *ibid.*, **60**, 2419 (1938).

(4a) For example, the temperature of ester decomposition is different in the two cases; also sulfur atoms are involved in the one instance, rather than oxygen.

namic instability of a double bond *exo* to a six-membered ring.⁵ If this assumption is correct it would follow from a deductive argument that the Chugaev elimination, and possibly ester pyrolyses in general, are governed in an important way by steric factors. Some evidence to support this conclusion was noted in the pyrolysis of the xanthate esters of methyl- and dimethylcyclohexylcarbinols.¹ Steric interaction between the two methyl groups and the adjacent axial hydrogens in dimethylcyclohexylcarbinol probably interferes with the xanthate grouping from becoming *cis* and *planar* with the 3° hydrogen in the cyclic transition state (Fig. A). This interference would not be as great as in the case of the monomethylcyclohexylcarbinol; hence both steric hindrance as well as the number of hydrogens available could explain why 38% of the *exo* isomer was produced, while only 21% of the *exo* isomer was formed in the case of dimethylcyclohexylcarbinol.

It was the purpose of this investigation to assess the importance of steric factors in ester pyrolyses. Toward this end a series of structurally related alcohols were dehydrated *via* their xanthate and acetate esters (equation 1). This series of com-



pounds was chosen with several considerations in mind. It will be noted that in the starting esters the carbon atom holding the ester group is flanked on both sides by a methylene group. If ester eliminations are essentially "non-selective,"⁶ statistical factors should be important in that the pseudo six-membered ring transition state should, by the laws of chance, form more often in the direction of the adjacent atom holding the larger number of hydrogen atoms.⁷ In our ester series this variable was held constant. It was deemed necessary also to choose a series of compounds such that the thermodynamic stability of the two olefins produced in each case would be essentially the same, since our previous work¹ had shown this to be an important variable in determining the direction of elimination. Heats of combustion data (Table III) which were available for all but one of the pairs of olefin products (see Isomerization Experiments below) indicated that indeed their stabilities were roughly identical in every case.

Isomerization Experiments.—Since there was no information available in the literature concerning the relative thermodynamic stabilities of 5,5-dimethyl-2-hexene and 2,2-dimethyl-3-hexene, an

(5) R. B. Turner and R. H. Garner, *THIS JOURNAL*, **80**, 1424 (1958).

(6) (a) E. Earl Royals, *J. Org. Chem.*, **23**, 1822 (1958); (b) D. H. Froemdsdorf, C. H. Collins, G. S. Hammond and C. H. De Puy, *THIS JOURNAL*, **81**, 643 (1959).

(7) See A. C. Cope and co-workers, *ibid.*, **79**, 4720 (1957), where statistical factors are discussed in connection with amine oxide decompositions.

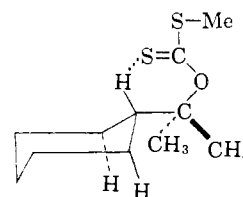


Fig. A.

attempt was made to obtain this information by equilibrating the two olefins. This proved difficult, since, in almost every case, there was a tendency for group migration as well as bond shifting. It was found, however, that the olefins could be passed over alumina at 350° from six to ten times with the occurrence of bond migration only. Additional passes resulted invariably in more extensive rearrangements. Table IV lists the results of these isomerizations. Pure samples of each olefin were used, as well as the mixture obtained from one of the pyrolysis runs. The results can be considered of qualitative value only since it is doubtful that true equilibrium had been attained. However, the average distribution of 40% 2,2-dimethyl-3-hexene and 60% 5,5-dimethyl-2-hexene indicates that either these olefins are of equal stability or possibly the 2-isomer is slightly more stable than the 3-. It would be highly desirable to have heats of hydrogenation data on these two isomers to establish their relative thermodynamic stability with greater certainty. In any event our isomerizations would indicate that the preferential formation of 2,2-dimethyl-3-hexene in the pyrolysis of the esters of 5,5-dimethyl-3-hexanol cannot be attributed to its greater thermodynamic stability.

TABLE I
PHYSICAL CONSTANTS OF ALCOHOLS AND ESTERS^a

Compounds	°C.	B.p. ^b	<i>n</i> _D ²⁰ ^b	Yield, %
3-Pentanol	113-114	(114.5) ^c	1.4090(1.4094) ^c	60
Acetate	132-134	(131) ^d	1.3965(1.3966) ^d	60
Xanthate	68-72	4 mm.	1.5318	28
3-Hexanol	132-134	(133) ^e	1.4140(1.4141) ^e	65
Acetate	150-151	(156) ^d	1.4041(1.4037) ^d	73
Xanthate	86-88	5 mm.	1.5203	25
5-Methyl-3-hexanol	146-148	(147-148) ^f	1.4171	60
Acetate	161-163	(162-164) ^f	1.4081	80
Xanthate	93-98	5 mm.	1.5136(27°)	30
5,5-Dimethyl-3-hexanol	61	20 mm.	1.4250(22°)(1.4250) ^g	68
Acetate	70	20 mm.	1.4120(23°)	91
Xanthate		Decomp.		

^a All esters were devoid of an alcohol band in the infrared. ^b The values in parentheses are literature values. ^c R. H. Pickard and J. Kenyon, *J. Chem. Soc.*, **103**, 1935 (1913). ^d J. Kenyon, *ibid.*, **105**, 2241 (1914). ^e G. Wagner, *Bull. soc. chim. France*, **42**, 330 (1884). ^f G. Wagner, *J. Russ. Phys. Chem. Soc.*, **16**, 287 (1885). ^g F. C. Whitmore, *et al.*, *THIS JOURNAL*, **60**, 2462 (1938).

With statistical factors constant in the starting esters, and the thermodynamic stability of the olefin products essentially the same, any trend noted in the direction of elimination as R is varied systematically from methyl to *t*-butyl can be attributed either to steric or electrical effects.

Analyses of Olefin Mixtures.—Each pyrolysis produced only two olefins (except the 3-pentanol esters; see Table II) although each of these was

TABLE II
 ESTER PYROLYSIS OF SECONDARY ALCOHOLS^a

Compound	Run	Pyrolysis temp., °C.	Olefin yield, % ^b	3-Olefin, %	2-Olefin, %
R = CH ₃					
3-Pentanol acetate	I	450	78		60 (t) 40(c)
	II	430	76		61 (t) 39(c)
Xanthate	I	250	89		63 (t) 37(c)
	II	250	89		63 (t) 37(c)
R = C ₂ H ₅					
3-Hexanol acetate	I	450	92	48 (33t) (15c) ^c	52 (35t) (17c) ^c
	II	420	85	47 (32t) (15c)	53 (36t) (17c)
Xanthate	I	250	83	50 (33t) (17c)	50 (34t) (16c)
	II	250	83	50 (34t) (16c)	50 (35t) (15c)
R = <i>i</i> -C ₃ H ₇					
5-Methyl-3-hexanol acetate	I	450	90	55 (50t) (5c)	45 (33t) (12c)
	II	450	84	56 (50t) (6c)	44 (33t) (11c)
Xanthate	I	200	86	55 (49t) (6c)	45 (34t) (11c)
	II	200	85	57 (51t) (6c)	43 (32t) (11c)
R = <i>t</i> -C ₄ H ₉					
5,5-Dimethyl-3-hexanol acetate	I	450	83	70 (65t) (5c)	30 (21t) (9c)
	II	425	86	70 (66t) (4c)	30 (21t) (9c)
Xanthate	I	150	84	69 (67t) (2c)	31 (25t) (6c)
	II	150	85	70 (68t) (2c)	30 (25t) (5c)

^a All analyses carried out by gas chromatography. ^b Yield of acetate reactions obtained by base titration of the acetic acid; xanthate yields obtained from olefin isolated. ^c The values in parentheses represent the percentage distribution between *cis* and *trans* isomers.

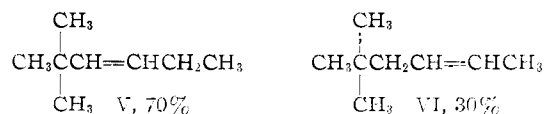
 TABLE III
 PHYSICAL CONSTANTS OF AUTHENTIC OLEFINS^a

Compound	B.p., ^b °C.	<i>n</i> _D ²⁰ ^b	Yield, % ^c	Olefin distribution, % ^d	Heats of combustion, kcal./mole ^k
5-Methyl-2-hexene (<i>cis</i>)	86-88(89.5)	1.4008(1.4000)	22 ^e	24	1118.38
	(<i>trans</i>) (88.1)	(1.4006)		76	1117.38
2-Methyl-3-hexene (<i>cis</i>)	84-85(86)	1.3992(1.3991)	4 ^e	15	1118.38
	(<i>trans</i>) (86)	(1.3991)		85	1117.38
5,5-Dimethyl-2-hexene (<i>cis</i>)	105-107(106.9)	1.4110(1.4113)	20 ^f	30
	(<i>trans</i>) (104.1)	(1.4055)		70	
2,2-Dimethyl-3-hexene (<i>cis</i>)	99-100(105.4)	1.4065(1.4069)	52 ^g	0
	(<i>trans</i>) (100.9)	(1.4063)		100	

^a 2-Pentene of 99 mole per cent. purity from Phillips Petroleum Co. was used. Vapor phase chromatography indicated it to contain 47% of the *cis* isomer and 53% *trans*. Authentic samples of the pure *cis* and *trans* isomers of 2-hexene and 3-hexene were obtained from the National Bureau of Standards. ^b The values in parentheses are taken from "Selected Values of Properties of Hydrocarbons and Related Compounds," National Bureau of Standards, U. S. Printing Office, Washington, D. C., 1952. ^c The values in this column are over-all yields in every instance. ^d Obtained by gas chromatography using β,β' -oxydipropionitrile or silver nitrate and triethylene glycol on Firebrick C-22, 30-60 mesh at 20 p.s.i. ^e Prepared by the "Boord synthesis"; see THIS JOURNAL, 52, 3396 (1930). ^f Prepared by coupling *t*-butylmagnesium chloride and crotyl bromide. ^g Prepared by the pyrolysis of the xanthate of 2,2-dimethyl-3-hexanol. ^h The heats of combustion of *cis* 2- and 3-hexene are 962.66 kcal./mole; for *trans* 2- and 3-hexene, 961.66 kcal./mole. These values are taken from "Selected Values of Properties of Hydrocarbons and Related Compounds," National Bureau of Standards, Washington, D. C., 1945.

formed in a *cis* and *trans* form. Analysis of the products was readily achieved by vapor phase chromatography. The four olefin peaks produced in every case were identified by comparing their retention times with authentic samples obtained by other methods. The sources of all of these authentic olefins are listed in Table III.

Discussion of Results.—It is obvious from the results listed in Table II that there is a decided trend in olefin distribution toward structure III (equation 1) as R is varied from methyl to *t*-butyl. This trend begins to be apparent when R is isopropyl (see 5-methyl-3-hexanol in Table II). We would judge the 55-45 olefin distribution in this case to be beyond experimental error. Of real significance, however, is the 70-30 olefin distribution noted in the case of 5,5-dimethyl-3-hexanol (see Table II and structures V and VI). For

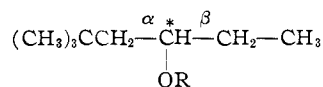


reasons noted earlier we feel confident that any trends which are apparent in this ester series are due to electrical or steric effects, since statistical factors and relative thermodynamic stability of the products are constant. Previously⁸ it was claimed that hydrogen acidities played an important role in determining the direction of ester eliminations, with the more acidic hydrogen the one preferentially removed. It is obvious that such an explanation cannot apply in our case. In fact, the trend noted in our ester series is exactly *opposite* to that predicted by relative hydrogen acidities.

(8) W. J. Bailey and L. Nicholas, *J. Org. Chem.*, 21, 648 (1952).

As R is varied from methyl to *t*-butyl (equation 1), the +I effect of the R group is progressively increasing and, as a consequence, the hydrogens on the adjacent methylene group should become more difficult to remove as a proton. Since this is contrary to the experimental findings, it would seem that electrical effects cannot be invoked to explain the results. One must conclude that either steric effects, or some other subtle, undefined factor is causing the trend in the eliminations. When R was ethyl (see 3-hexanol entry, Table II) the observed olefin distribution was roughly 50–50 within experimental error. When R was isopropyl (see 5-methyl-3-hexanol, Table II) the distribution became approximately 55–45. However, when R was *t*-butyl (see 5,5-dimethyl-3-hexanol), the distribution changed abruptly to 70–30. Such abrupt changes in passing from an isopropyl to *t*-butyl group have been noted in other systems,⁹ and are usually attributable to a steric effect. Although the isopropyl group possesses two bulky methyl groups, it also carries one hydrogen and, as a consequence, can orient itself in such a way as to minimize the bulk of the two methyl groups. The *t*-butyl, being a symmetrical group, cannot do this, and hence shows a much greater steric effect than the isopropyl.

Steric Effect in Ester Elimination.—It will be noted that the esters of 5,5-dimethyl-3-hexanol possess an asymmetric carbon which is capable of a *d*- and *l*-configuration. For the purposes of this



discussion it will be necessary to center attention on one of these configurations only, since the conclusions reached with regard to the one will hold for the other also. By sighting along the α -bond of the

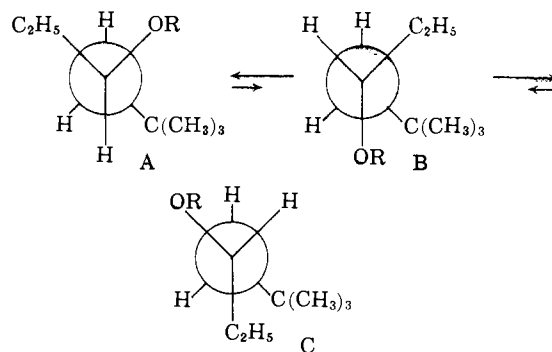
TABLE IV

Starting olefin ^b	2,2-Dimethyl-3-hexene, %		5,5-Dimethyl-2-hexene, %	
	<i>trans</i>	<i>cis</i>	<i>trans</i>	<i>cis</i>
2,2-Dimethyl-3-hexene	26	16	33	25
5,5-Dimethyl-2-hexene	20	13	47	20
Olefin mixt. from the pyrolysis of 5,5-dimethyl-3-acetoxy-hexane	36	8	36	20
Average value	28	12	38	22

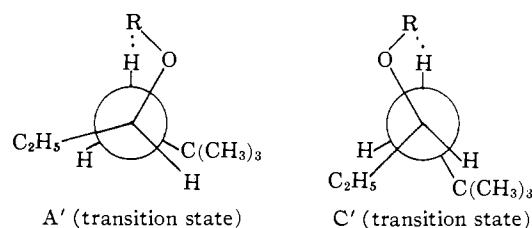
^a All olefin distributions were obtained by gas chromatography; for conditions see Experimental. ^b The percentages listed are values obtained after 6 to 10 passes through an alumina column.

ester shown above from the asymmetric carbon toward the *t*-butyl group, the three conformations pictured below are possible. It will be noted that conformations A and C are constituted so as to have only one large group (OR or C₂H₅) adjacent to the very bulky *t*-butyl group. Conformations A and C should be considerably more favorable than B (because of the adjacent OR, -C(CH₃)₃, and -C₂H₅ in B). In addition, conformation B

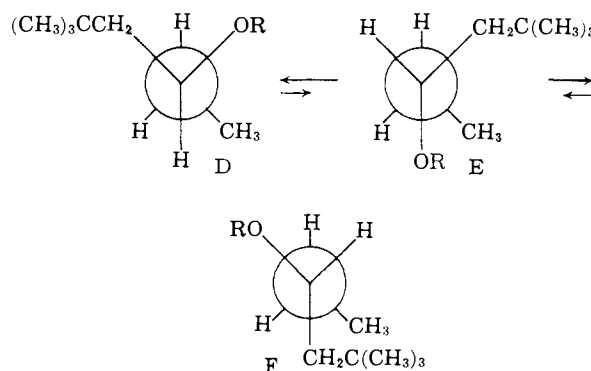
(9) H. C. BROWN and R. H. HOROWITZ, THIS JOURNAL, **77**, 1733 (1955).



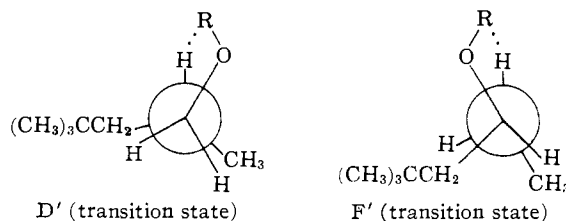
would lead only to a *cis*-olefin product, which experimentally forms only in minor amounts (Table II). Hence B can be eliminated from further consideration. By appropriate eclipsing of groups, transition states for A and C can be pictured which will lead to the formation of *trans*-2,2-dimethyl-3-hexene (V), the predominant product of the reaction.



In a similar fashion, by sighting along the β -bond from the asymmetric carbon toward the methyl group, conformations D, E and F can be drawn, of which only D and F need be considered.



Again, by eclipsing of groups, transition states for D and F can be pictured which will lead to *trans*-5,5-dimethyl-2-hexene (VI), the minor product.



It should be noted that when conformation A moves into its transition state A' there is some steric assistance provided by the separation of the ester and *t*-butyl groups. Similarly as C moves

to C' it is sterically assisted by the separation of the ethyl and *t*-butyl groups.¹⁰

Steric assistance of this magnitude is not provided when D and F move toward D' and F'. Stated another way, the activation energy required to reach the transition state is less in the formation of 2,2-dimethyl-3-hexene (V) than that required for the formation of 5,5-dimethyl-2-hexene (VI). Thus, steric assistance provides for the easier attainment of a *cis* coplanar transition state in the formation of V, while in the case of dimethylcyclohexylcarbinol discussed previously, steric factors may be hindering the formation of such a transition state (see Fig. A).¹¹

Recently⁶ it was reported that pyrolysis of the acetate of 4-methyl-2-pentanol results in a 55% distribution of 4-methyl-2-pentene and 45% 4-methyl-1-pentene. A conformational analysis, employing the steric arguments invoked above, explain this isomer distribution very nicely. This represents a case of conflicting effects, however, in that statistical factors tend to favor the formation of 4-methyl-1-pentene while both thermodynamic stability and conformational effects favor formation of 4-methyl-2-pentene. Apparently the latter two effects are able to override the influence of the former.

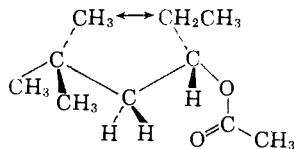
Pyrolysis of 2-heptyl acetate produces a ratio of 1-heptene/2-heptene of 1.1.⁶ If statistical factors alone were operating in this case, a ratio of 1.5 would be predicted. Very likely the statistical factor is partially nullified by the fact that 2-heptene is more thermodynamically stable than 1-heptene. Hence the ratio of the two isomers is reduced practically to unity. Conformational effects in this case are probably of little importance.

Still other examples^{1,12} can be found where the thermodynamic stability of the two olefin products is so vastly different as to become the overriding factor in determining the direction of elimination. In this paper we have presented examples wherein we feel conformational effects are the controlling feature.

It should be borne in mind that the above proposals are offered purely as hypotheses at the present time. It remains for future work to establish their validity.

Summary.—It is suggested that the direction of elimination in ester pyrolyses is governed by the

(10) The same situation can be represented by a three dimensional side view of the staggered conformation C. This view illustrates more specifically where the interaction occurs.



This interesting observation and the subsequent arguments that are derived from it were brought to our attention by Dr. James H. Brewster.

(11) Recently (ref. 6b) a similar idea has been proposed. It was suggested that the close agreement between the product distribution obtained in the pyrolysis of *t*-amyl acetate and that calculated for the random process is due partly to the cancellation of thermodynamic stability effects (which would favor formation of trimethylethylene) and the transition state eclipsing effect which would favor production of the terminal olefin.

(12) C. H. DePuy and R. E. Leary, *THIS JOURNAL*, **79**, 3705 (1957).

interplay of three factors: (1) statistical effects (*i.e.*, the number of hydrogens available on each of the carbon atoms flanking the ester group), (2) relative thermodynamic stability of the two olefin products, (3) steric effects, wherein either steric assistance or steric interference is afforded the formation of the cyclic, coplanar¹³ transition state.

Experimental

Synthesis of Alcohols.—In general all of the alcohols listed in Table I were prepared by reaction of the appropriate Grignard reagent with propionaldehyde. The directions given below for the preparation of 5,5-dimethyl-3-hexanol can be taken as typical of all. Table I lists the physical constants of these alcohols together with their acetates and xanthates.

5,5-Dimethyl-3-hexanol.—Neopentylmagnesium chloride was prepared in the usual manner using 213 g. (2 moles) of neopentyl chloride¹⁴ and 48 g. (2 g. atoms) of magnesium turnings with 600 ml. of ether. To this Grignard reagent, 116 g. (2 moles) of freshly distilled propionaldehyde in 300 ml. of ether was added. The product was worked up in the usual manner and the alcohol was fractionated in an 18-in. Widmer column. There was obtained 175 g. (68%) of 5,5-dimethyl-3-hexanol (b.p. 61° (20 mm.), n_D^{20} 1.4250).

Anal. Calcd. for C₈H₁₈O: C, 73.84; H, 13.84. Found C, 73.93; H, 13.50.

Olefin Syntheses.—Table III lists the sources of all of the olefins used in this study along with their physical constants. It will be noted that in two instances the standard Boord alkene synthesis¹⁵ was employed. The synthesis of 5,5-dimethyl-2-hexene and 2,2-dimethyl-3-hexene was achieved in a different fashion and is accordingly described below.

5,5-Dimethyl-2-hexene.—*t*-Butylmagnesium chloride (0.5 mole) was prepared in the usual manner and 60 g. (0.45 mole) of freshly distilled crotyl bromide was added slowly. The mixture was stirred for 52 hours and worked up in the usual manner. The ether was distilled off and the olefin mixture was fractionated in a Todd column (20:1 reflux ratio). Each of seven fractions boiling from 101 to 107° was analyzed by gas chromatography. It was found that fractions 5, 6 and 7 were 90% *cis*- and *trans*-5,5-dimethyl-2-hexene. The physical constants are listed in Table III. The other component, boiling at 103–105°, very likely was the rearranged product, 3,4,4-trimethyl-1-pentene which boils at 104°. The yield of 5,5-dimethyl-2-hexene was 10 g. (20%).

2,2-Dimethyl-3-hexene.—2,2-Dimethyl-3-hexanol was prepared by treating 1 mole of *t*-butylmagnesium chloride with freshly distilled butyraldehyde (1 mole). The yield was 65 g. (50%), b.p. 152–155°.

The xanthate ester (48 g., 63% yield) was prepared as described by Boord.¹⁶ It distilled at 75–78° (1 mm.), n_D^{20} 1.5125. The reported constants¹⁶ for this compound are b.p. 112–114° (8 mm.), n_D^{20} 1.5122.

The xanthate ester was pyrolyzed yielding 20 g. (82%) of pure olefin. The over-all yield was 52%. The physical constants are listed in Table III.

Chugaev Reactions.—The Whitmore¹⁷ modification of the Chugaev reaction was employed using 0.25–0.3 mole of alcohol, 150 ml. of ether and 12.5 ml. of carbon tetrachloride. The mixture was treated with an equimolar amount of sodium hydroxide to form the sodium salt. Then an equimolar amount of carbon disulfide was added slowly while the temperature was kept below 30°. After three hours of stirring, an equimolar amount of methyl iodide was added dropwise, and the mixture was stirred and refluxed for 6 hours. It was distilled under vacuum in a 6-in. Widmer

(13) The discussion in this paper in no way is meant to invalidate or detract from the importance of a *cis*-hydrogen requirement in ester eliminations. It is well established that these reactions proceed so as to remove *cis*-hydrogens when possible (E. R. Alexander and A. Mudrak, *ibid.*, **72**, 1810 (1950)). This point has been assumed throughout our paper.

(14) F. C. Whitmore and G. Fleming, *ibid.*, **55**, 4161 (1933).

(15) H. B. Dykstra, J. F. Lewis and C. E. Boord, *ibid.*, **52**, 3396 (1930).

(16) J. Schurman and C. E. Boord, *ibid.*, **55**, 4930 (1933).

(17) F. C. Whitmore and C. T. Simpson *ibid.*, **55**, 3809 (1933).

column. The yield and boiling point are given in Table I. An infrared spectrum of the xanthates showed the absence of -OH bands.

The ester was then pyrolyzed in a 50-ml. flask attached to an 18-in. Vigreux column at approximately 200°. The olefin was collected in a cooled receptacle and the mercaptan was trapped in a saturated solution of barium hydroxide. A free flame was found to offer the best control of foaming in the decomposition of the xanthate. The resulting olefins were analyzed by gas chromatography.

Preparation and Pyrolysis of Acetates.—The acetates were prepared by the action of 300 ml. of pure acetic anhydride and 10 ml. of dry pyridine on 0.75 mole of the corresponding alcohol. The mixture was heated on a steam-bath for two hours and then poured into ice-water. The oily layer which formed was separated and then washed with water and extracted with ether. The ether was evaporated under vacuum and the acetate was fractionally distilled; see Table I for physical constants.

The acetates were pyrolyzed in conventional fashion according to the method of Bailey.¹⁸ The results are listed in Table II.

(18) W. J. Bailey and C. King, *J. Org. Chem.*, **21**, 858 (1956).

Isomerization Experiments.—Approximately 10 g. of 5,5-dimethyl-2-hexene, 2,2-dimethyl-3-hexene and the olefin mixture obtained from the pyrolysis of 5,5-dimethyl-3-acetoxyhexane, were passed independently through an alumina (Alcoa F-20) column, 1" in diameter and 12" long at 350°. Each olefin was passed through the column from 6 to 10 times under a slight nitrogen pressure. The olefins were collected in a trap at -78° and were analyzed after each run by gas chromatography. A Fisher-Gulf partitioner was employed with a flow rate of helium from 10 to 20 ml./min.; chart speed, 1/4 in./min.; pressure, 20 p.s.i.; temperature, 67°; sensitivity, 40 to 50%; column packing, 50% β,β' -oxydipropionitrile on Fisher Columpak 30-60 mesh; column length, 14 ft; sample volume, 0.001 to 0.005 ml. The results of these isomerizations are listed in Table IV.

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LAFAYETTE, IND.

[CONTRIBUTION FROM THE CHEMISTRY DIVISION OF OAK RIDGE NATIONAL LABORATORY]

The Isotope Effect and its Relation to the Validity of Isotopic Tracer Experiments¹

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The ORACLE¹¹ has been employed to determine, for first-order irreversible reactions, the relation between fraction of reaction ($f = 1 - e^{-kt}$) and the accumulated product ratio $R \left(R = \frac{1 - e^{-k^*t}}{1 - e^{-kt}} \right)$ over a range of values for the isotope effect (k^*/k) of 0.05 to 0.99. Similar calculations have been made for f as a function of the ratio (α) of the differentials of the fractions of labeled to unlabeled molecules formed. All results are presented graphically, and are discussed with respect to their possible effect upon the validity of certain experiments with isotopic elements.

The isotopes of carbon have been widely used as tracers in the study of organic and biochemical reactions.² Deuterium and tritium also have been employed in mechanism studies,^{2b} the tritium being nearly always in trace concentrations.³ The difference in reaction rate between labeled and unlabeled compounds—that is, the isotope effect—pertains to tracer chemistry in at least three ways: (1) in determinations of the slow or so-called "rate-determining steps" of many reactions,^{3,4} (2) in the study of hyperconjugation,^{5,6} and (3) because of

the possible doubt which might be cast upon the validity of tracer experiments when the manner of operation of the isotope effect is not clearly understood.

The general theory of homocompetitive reactions is well known,^{7,8} and has been applied to the field of isotopic chemistry by Bigeleisen⁹ and by Melander,¹⁰ who have drawn attention to some of the errors which can arise in tracer experiments because of the "lagging" of the heavy isotope.¹⁰

In the present paper we wish to enlarge upon the discussions of Bigeleisen⁹ and Melander¹⁰ by presenting the results of calculations carried out with the assistance of the ORACLE,^{10a} which will show how the ratio of product from labeled reactant to product from unlabeled reactant varies over a wide range of isotope effect values. These calculations will illustrate several types of error which can be introduced into tracer experiments;

(1) This paper is based upon work performed at Oak Ridge National Laboratory, which is operated for the Atomic Energy Commission by Union Carbide Corporation.

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(3) L. Melander, *Arkiv Kemi*, **2**, 211 (1950).

(4) (a) K. B. Wiberg, *Chem. Revs.*, **55**, 713 (1955); (b) G. A. Ropp, *Nucleonics*, **10**, 22 (1952); (c) P. E. Yankwich, *Ann. Rev. Nuclear Sci.*, **3**, 235 (1953); (d) V. Gold and D. P. N. Satchell, *Quart. Revs.*, **9**, 51 (1955).

(5) V. J. Shiner, *THIS JOURNAL*, **74**, 5285 (1952); **75**, 2925 (1953); **76**, 1603 (1954); **78**, 2653 (1956); V. J. Shiner and S. Cross, *ibid.*, **79**, 3599 (1957).

(6) E. S. Lewis and C. E. Boozer, *ibid.*, **74**, 6307 (1952); **76**, 791 (1954); C. E. Boozer and E. S. Lewis, *ibid.*, **76**, 794 (1954); E. S. Lewis and G. M. Coppinger, *ibid.*, **76**, 4495 (1954).

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(8) T. S. Lee, "Rates and Mechanism of Reactions," Interscience Publishers, Inc., New York, N. Y., 1953, pp. 100-130.

(9) (a) J. Bigeleisen, *Science*, **110**, 14, 149 (1949); (b) J. Bigeleisen and M. Wolfsberg in "Advances in Chemical Physics," Vol. 1, Interscience Publishers, Inc., New York, N. Y., 1958, pp. 35-53.

(10) Reference 3, pp. 248-257.

(10a) Oak Ridge Automatic Computer and Logical Engine.