THE *syn-anti* DICHOTOMY IN BIMOLECULAR ELIMINATION OF ALKYLTRIMETHYLAMMONIUM SALTS: STERIC AND POLAR EFFECTS ON RATES AND ORIENTATION IN THE COMPETING PATHWAYS*

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The title problem has been investigated in two homologous series of positionally isomeric alkyltrimethylammonium salts, $RCH_2CHXC_5H_{11}^{(+)}$ and $RCHXCH_2C_5H_{11}^{(-)}$ (R = H, CH_3, C_2H_5, n-C_3H_7, iso-C_3H_7 and tert-C_4H_9; X = $N(CH_3)_3Cl$), employing potassium tert-butoxide in tert-butanol and also potassium methoxide in methanol as the base–solvent combination. The overall rate constants of the individual olefin-isomer formation have been determined in these series and dissected, approximately, into the *syn*- and *anti*-components. The alkyl structure–reactivity relationship is thus obtained separately for the two complementary mechanisms of bimolecular elimination. The long-standing question whether steric or polar influence of alkyl group dominates in the complex reaction is re-examined on these grounds. Contrary to earlier extreme views it is shown that both the steric as well as the polar effects are very important, the former being operative mainly in the stereochemical (*syn–anti*) whereas the latter in the orientational (Hofmann–Saytzeff) control of the dichotomous reaction.

The question whether steric or polar effects dominate the kinetic and orientational pattern of E2 reaction of alkyltrimethylammonium salts was the main issue in the well-known discussion between the founders of steric and polar school (Brown–Ingold controversy)[2-4]; however, the opposing views remained unresolved. The discovery that the quaternary salts do not eliminate uniformly by the *anti*-mechanism, as it was originally assumed, but exploit simultaneously two mechanistic channels[5-17] (*anti* and *syn*) placed the "old" problem in a new light; it showed, in particular, that meaningful conclusions on the operation of steric and/or polar effects in the reaction can be obtained only when the alkyl structure–reactivity relationships in the two competing pathways are separately examined.

This poses, obviously, a task of a considerable complexity which can be approached unambiguously only by combination of kinetic data from appropriate homologous

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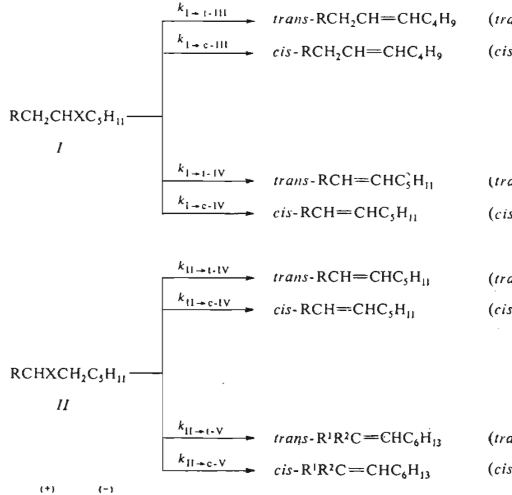
series with the corresponding "static" data concerning the *syn*- and *anti*-contributions to the individual olefin-isomer formation. The earlier approaches[3,8–10] based only on the kinetic[3] or on the "static"[7,8] data are bound to be uncertain and lead, eventually, to one-sided or entirely incorrect conclusions.

In this paper we report such a complex analysis for the reaction of two homologous series of positionally isomeric alkyltrimethylammonium salts *I* and *II* (Scheme 1) with potassium tert-butoxide in tert-butanol and also with potassium methoxide in methanol. In the first step, the partial rate constants for the individual olefin-isomer formation from *I* ($k_{I\to t-III}$, $k_{I\to c-III}$, $k_{I\to t-IV}$, $k_{I\to c-IV}$) and from *II* ($k_{II\to t-IV}$, $k_{II\to c-IV}$, $k_{II\to t-V}$, $k_{II\to c-V}$) were determined in the two base–solvent combinations by standard kinetic procedures employing an efficient gas-chromatographic technique. In the next step, the rate constants were dissected into the *syn*- and *anti*-components. In some cases, the dissection was performed quantitatively, on basis of the reported *syn*- and *anti*-contributions in the particular olefin-forming process. In the other cases, when the direct data were not available, we used the reported data from closely similar elimination situations as approximation in the calculation.



SCHEME 1

In this way, alkyl structure–reactivity relationship was determined approximately for the competing *syn*- and *anti*-pathways. Analysis of steric and polar effects controlling the dichotomous reaction is performed on these grounds.

EXPERIMENTAL

Alkyltrimethylammonium Iodides

5-Decyl, 2,2-dimethyl-3-nonyl and 2,2-dimethyl-4-nonyl derivatives were available from the previous work[11,12]. Other quaternary iodides were prepared from the corresponding alkyldimethylamines[13] by treating with methyl iodide in benzene under standard conditions in nearly quantitative yields. Melting points and elemental analyses are summarized in Table I.

TABLE I
Alkyltrimethylammonium Iodides

Alkyl	M.p., °C	Formula (m.w.)	Calculated/Found		
			% C	% H	% N
1-Heptyl	141—143	$C_{10}H_{24}IN$	42·11	8·48	4·91
		(285·2)	41·80	8·42	4·54
2-Heptyl	196—197	$C_{10}H_{24}IN$	42·11	8·48	4·91
		(285·2)	42·02	8·51	4·68
2-Octyl	231—232	$C_{11}H_{26}IN$	44·15	8·76	4·68
		(299·2)	44·41	8·89	4·87
3-Octyl	217—219	$C_{11}H_{26}IN$	44·15	8·76	4·68
		(299·2)	43·85	8·72	4·38
3-Nonyl	236—237	$C_{12}H_{28}IN$	46·00	9·01	4·47
		(313·3)	46·19	8·96	4·66
4-Nonyl	210—212	$C_{12}H_{28}IN$	46·00	9·01	4·47
		(313·3)	46·26	9·13	4·78
4-Decyl	211—213	$C_{13}H_{30}IN$	47·70	9·24	4·28
		(327·3)	47·80	9·20	3·95
2-Methyl-3-nonyl	220—221	$C_{13}H_{30}IN$	47·70	9·24	4·28
		(327·3)	47·76	9·26	4·54
2-Methyl-4-nonyl	142—144	$C_{13}H_{30}IN$	47·70	9·24	4·28
		(327·3)	47·95	9·28	4·41

Alkyltrimethylammonium Chlorides

Prepared from the quaternary iodides by shaking with an excess of silver chloride in methanol. A usual work-up[14] afforded the products in practically quantitative yields. The quaternary chlorides were hygroscopic; before use, they were dried on the oil pump and stored in desiccator over P_2O_5.

Rate Measurements

The overall rates of the decomposition (E2 + S_N2) were measured gas-chromatographically by determining the increase in concentration of the reaction products with time, using the method of internal standard[13,15]. The rates of the partial processes (alkyldimethylamine and individual olefin-isomer formation) were calculated from the overall rate constants and from the yields of the particular products again as determined by gas chromatography.

Determination of the overall rates and product composition: About 150–200 mg of the quaternary chloride was accurately weighed and dissolved in the alkoxide–alcohol solution (100 ml) containing a known amount of the internal standard (n-propylcyclopentane and 2- or 3-octyldimethylamine for determination of alkenes and alkyldimethylamine, respectively). The solution was distributed into dried ampoules (5 ml lots), the ampoules were flushed with nitrogen, sealed and placed into a thermostated bath. In appropriate time intervals the ampoules were withdrawn and the reaction was quenched by pouring the contents in 50 ml volumetric flask containing 1M-KOH in saturated aqueous sodium chloride solution (20 ml) and pentane (1 ml). The volumes were made up to mark with water, the contents were shaken and a sample of the pentane layer was injected into the gas chromatograph. According to the internal standards, the sum of areas corresponding to alkenes (E2) and to alkyldimethylamine (S_N2), determined at the time t_∞, accounted in all cases satisfactorily (±5%) for the overall reaction. The product composition data are summarized in Tables II–V.

Evaluation of the rate data: The reaction was carried out in a large excess of the alkoxide base so that the second-order rate constant for the overall (E2 + S_N2) reaction can be calculated from the gas-chromatographic data using the expression[13,15] (*1*):

$$k_2^{tot} = (2{\cdot}303/t \,.\, b) \log \left[R_\infty/(R_\infty - R_t)\right], \qquad (1)$$

where b is the concentration of the potassium alkoxide; R_t and R_∞ are values expressing the ratios of the integrated areas corresponding respectively to a given product* and to the internal standard, at the time t (R_t) or at the end of the reaction (R_∞) as determined by gas chromatography. The decomposition was measured on average up to 80% completion and the overall rate constants were evaluated numerically. Reproducibility was about ±5%.

The rate constants of the total E2 process, k_{E2}^{tot}, and the rate constants of the accompanying S_N2 process, k_{SN2}, were calculated from the overall rate constants of decomposition according to Eqs (*2*) and (*3*):

$$k_{E2}^{tot} = (\%\ E2)\, k_2^{tot}/100\,, \qquad (2)$$

* In principle, any single product, or sum of the products can be used in the calculation of k_2^{tot}: *cf.* ref.[15] We used, in most cases the sum of the areas corresponding to all the resulting olefin-isomers.

$$k_{S_N2} = (\% S_N2)\, k_2^{tot}/100\,, \qquad (3)$$

where % E2 and % S_N2 are the percentages of alkenes and alkyldimethylamine, respectively, determined at the end of the reaction (Table II—V).

TABLE II

Product Composition from the Reaction of the Alkyltrimethylammonium Chlorides *I*, $RCH_2.\overset{(+)}{C}H[\overset{(-)}{N}(CH_3)_3Cl].C_5H_{11}$, with 0·435M Potassium Tert-Butoxide in Tert-Butanol at 35°C

R	% S_N2[a]	% E2[b]	$RCH_2CH{=}CHC_4H_9$ (*III*)		$RCH{=}CHC_5H_{11}$ (*IV*)	
			% *trans*	% *cis*	% *trans*	% *cis*
H	~5·3	~90	~ 0·2	~ 0·8	~99[c]	
CH_3	46·8	61·0	17·9	6·1	31·5	44·5
C_2H_5	62·2	42·0	36·6	10·8	40·0	12·6
n-C_3H_7	60·2	41·3	~36·5	~13·5	~36·5	~13·5
i-C_3H_7	67·2	33·8	69·6	15·8	13·9	0·7
t-C_4H_9	46·8	58·5	96·0	1·7	2·3	~ 0·01

[a] Percentage of the corresponding alkyldimethylamine *I*; X = $N(CH_3)_2$. [b] Overall percentage of alkenes. Aside from the isomers indicated in the Table, no other olefins were found in the reaction mixture. [c] Percentage of the terminal isomer in the olefin mixture.

TABLE III

Product Composition from the Reaction of the Alkyltrimethylammonium Chlorides *II*, $RCH[\overset{(+)}{N}(CH_3)_3\overset{(-)}{C}l].CH_2C_5H_{11}$, with 0·435M Potassium Tert-Butoxide in Tert-Butanol at 35°C

R	% S_N2[a]	% E2[b]	$RCH{=}CHC_5H_{11}$ (*IV*)		$R^1R^2C{=}CHC_6H_{13}$ (*V*)	
			% *trans*	% *cis*	% *trans*	% *cis*
H	68·0	37·3	100[c]		—	—
CH_3	4·7	89·4	~ 0·3	~ 1·2	98·5[c]	
C_2H_5	44·2	52·5	18·0	6·5	32·5	43·0
n-C_3H_7	59·8	38·7	~36·6	~10·8	~40·0	~12·6
i-C_3H_7	72·2	26·9	79·0	1·6	19·4[d]	
t-C_4H_9	88·8	5·5	96·4	3·6	—	—

[a] Percentage of the corresponding alkyldimethylamine *II*; X = $N(CH_3)_2$. [b] Overall percentage of alkenes. Aside from the isomers indicated in the Table, no other olefins were found in the reaction mixture. [c] Percentage of the terminal isomer. [d] Percentage of the trisubstituted isomer.

TABLE IV

Product Composition from the Reaction of the Alkyltrimethylammonium Chlorides *I*, $\overset{(+)}{R}CH_2CH[\overset{(-)}{N}(CH_3)_3Cl].C_5H_{11}$, with 2·02M Potassium Methoxide in Methanol at 115°C

R	% S_N2[a]	% E2[b]	$RCH_2CH{=}CHC_4H_9$ (*III*)		$RCH{=}CHC_5H_{11}$ (*IV*)	
			% *trans*	% *cis*	% *trans*	% *cis*
H	17·0	72·2	1·3	3·8	94·9[c]	
CH_3	47·0	50·9	5·3	18·6	19·6	56·5
C_2H_5	56·0	38·9	9·3	38·3	10·6	41·8
n-C_3H_7	57·0	38·6	~9·8	~40·2	~9·8	~40·2
i-C_3H_7	67·0	30·3	17·2	60·8	10·8	11·2
t-C_4H_9	72·5	20·6	39·6	54·0	5·5	0·9

[a] Percentage of the corresponding alkyldimethylamine *I*; X = $N(CH_3)_2$. [b] Overall percentage of alkenes. Aside from the isomers indicated in the Table, no other olefins were found in the reaction mixture. [c] Percentage of the terminal isomer.

TABLE V

Product Composition from the Reaction of the Alkyltrimethylammonium Chlorides *II*, $\overset{(+)}{R}CH[\overset{(-)}{N}(CH_3)_3Cl].CH_2C_5H_{11}$, with 2·02M Potassium Methoxide in Methanol at 115°C

R	% S_N2[a]	% E2[b]	$RCH{=}CHC_5H_{11}$ (*IV*)		$R^1R^2C{=}CHC_6H_{13}$ (*V*)	
			% *trans*	% *cis*	% *trans*	% *cis*
H	74·5	12·1	100[c]		—	—
CH_3	14·5	74·0	1·3	3·9	94·8[c]	
C_2H_5	37·5	49·9	5·9	18·7	19·8	55·6
n-C_3H_7	50·0	35·8	~10·0	~40·0	~10·0	~40·0
i-C_3H_7	48·0	42·5	21·3	5·9	72·8[d]	
t-C_4H_9	78·8	9·2[e]	42·6	57·4[e]	—	—

[a] Percentage of the corresponding alkyldimethylamine *II*; X = $N(CH_3)_2$. [b] Overall percentage of alkenes. Unless indicated otherwise, only the isomers indicated in the Table were found in the reaction mixture. [c] Percentage of the terminal isomer. [d] Percentage of the trisubstituted isomer. [e] A decrease in the *cis*-isomer proportion and formation of two additional olefinic products was noted on lowering the methoxide concentration (0·5M). A quite analogous situation was found in elimination of the corresponding tosylate (X = OTs) and explained by incursion of E1 process; *cf.* ref.[16].

The rate constants of the individual olefin-isomer formation, k^{i}_{E2}, were calculated from the rate constants of the total E2 process according to Eq. (*4*):

$$k^{i}_{E2} = (\%\,i)\, k^{tot}_{E2}/100\,, \qquad (4)$$

where %i is the percentage of the particular olefin isomer in the resulting alkene mixture (Tables II–V). The partial rate constants k^{tot}_{E2}, k_{SN2}, and k^{i}_{E2} are summarized in Tables VI–IX.

TABLE VI

Partial Rate Constants (in l mol^{-1} s^{-1}) in the Reaction of Alkyltrimethylammonium Chlorides *I*, $\overset{(+)}{RCH_2CH}[\overset{(-)}{N(CH_3)_3Cl}].C_5H_{11}$, with 0·43M Potassium Tert-Butoxide in Tert-Butanol as 35°C

R	$10^7 k_{SN2}$	$10^7 k^{tot}_{E2}$	$RCH_2CH{=}CHC_4H_9$ (*III*)		$RCH{=}CHC_5H_{11}$ (*IV*)	
			$10^7 k_{I\to t-III}$	$10^7 k_{I\to c-III}$	$10^7 k_{I\to t-IV}$	$10^7 k_{I\to c-IV}$
H	239	4 050	~8·1	~32·4	~4 010[a]	
CH_3	342	445	79·8	27·2	140·0	198·0
C_2H_5	339	229	83·8	24·8	91·6	28·8
n-C_3H_7	386	264	96·4	35·6	96·4	35·6
i-C_3H_7	430	216	150·4	34·1	30·0	1·5
t-C_4H_9	360	450	432	7·6	10·3	0·05

[a] The rate constant of 1-heptene formation.

TABLE VII

Partial Rate Constants (in l mol^{-1} s^{-1}) in the Reaction of Alkyltrimethylammonium Chlorides *II*, $\overset{(+)}{RCH}[\overset{(-)}{N(CH_3)_3Cl}].CH_2C_5H_{11}$, with 0·43M Potassium Tert-Butoxide in Tert-Butanol at 35°C

R	$10^7 k_{SN2}$	$10^7 k^{tot}_{E2}$	$RCH{=}CHC_5H_{11}$ (*V*)		$R^1R^2C{=}CHC_6H_{13}$ (*V*)	
			$10^7 k_{II\to t-IV}$	$10^7 k_{II\to c-IV}$	$10^7 k_{II\to t-V}$	$10^7 k_{II\to c-V}$
H	93	51	51[a]		—	—
CH_3	251	4 780	14·4	57·6	4 708[b]	
C_2H_5	367	435	78·2	28·3	141·5	187
n-C_3H_7	383	248	~90·8	~26·8	~99·1	~31·3
i-C_3H_7	600	224	177·0	3·6	43·4[c]	
t-C_4H_9	2 940	183	176·4	6·6	—	—

[a] The rate constant of 1-heptene formation. [b] The rate constant of 1-octene formation. [c] The rate constant of the trisubstituted alkene formation ($R^1 = R^2 = CH_3$).

Dissection of rate constants of the individual olefin-isomer formation into the syn- *and the* anti-*components*: The dissection was made using the Eqs (*5*) and (*6*):

$$k^{syn} = (\%\ syn)\, k^{i}_{E2}/100\,, \qquad (5)$$

$$k^{anti} = (\%\ anti)\, k^{i}_{E2}/100\,, \qquad (6)$$

TABLE VIII

Partial Rate Constants (in l mol^{-1} s^{-1}) in the Reaction of Alkyltrimethylammonium Chlorides *I*, $RCH_2\overset{(+)}{C}H[\overset{(-)}{N}(CH_3)_3Cl].C_5H_{11}$, with 2·02M Potassium Methoxide in Methanol at 115°C

R	$10^7 k_{SN2}$	$10^7 k^{tot}_{E2}$	$RCH_2CH{=}CHC_4H_9$ (*III*)		$RCH{=}CHC_5H_{11}$ (*IV*)	
			$10^7 k_{I\to t-III}$	$10^7 k_{I\to c-III}$	$10^7 k_{I\to t-IV}$	$10^7 k_{I\to c-IV}$
H	192	816	10·6	31·0	774·4[a]	
CH_3	258	290	15·3	53·9	56·8	164
C_2H_5	224	155	14·4	59·4	16·4	64·8
C_3H_7	210	142	~13·9	~57·1	~13·9	~57·1
i-C_3H_7	222	100	17·2	60·8	10·8	11·2
t-C_4H_9	217	61·6	24·4	33·2	3·4	0·6

[a] The rate constant of 1-heptene formation.

TABLE IX

Partial Rate Constants (in l mol^{-1} s^{-1}) in the Reaction of Alkyltrimethylammonium Chlorides *II*, $RC\overset{(+)}{H}[\overset{(-)}{N}(CH_3)_3Cl].CH_2C_5H_{11}$, with 2·02M Potassium Methoxide in Methanol at 115°C

R	$10^7 k_{SN2}$	$10^7 k^{tot}_{E2}$	$RCH{=}CHC_5H_{11}$ (*IV*)		$R^1R^2C{=}CHC_6H_{13}$ (*V*)	
			$10^7 k_{II\to t-IV}$	$10^7 k_{II\to c-IV}$	$10^7 k_{II\to t-V}$	$10^7 k_{II\to c-V}$
H	104	17	17·0[a]		—	—
CH_3	171	872	11·3	34·1	827[b]	
C_2H_5	208	277	16·3	51·8	54·8	154·0
n-C_3H_7	206	147	~14·7	~58·8	~14·7	~58·8
i-C_3H_7	276	244	52·0	14·4	177·6[c]	
t-C_4H_9	710	83	35·4	47·6	—	—

[a] The rate constant of 1-heptene formation. [b] The rate constant of 1-octene formation. [c] The rate constant of the trisubstituted alkene formation ($R^1 = R^2 = CH_3$).

where % *syn* and % *anti* are the contributions of the *syn*- and *anti*-pathways, respectively, corresponding to the particular olefin-forming process. The contribution used in the present calculation are summarized in Tables X and XI. As it follows from the footnotes to Tables X and XI, only for a part of the processes now under study (*I* → *trans-III*; R = n-C_3H_7 and t-C_4H_9, *I* → *trans-IV*; R = t-C_4H_9, *II* → *trans-IV*; R = t-C_4H_9), the dissection could be performed quantitatively, on basis of the direct experimental data reported[11,12] by us previously both for the tert-butoxide and for the methoxide base. For the other processes, where the direct data were not available, the *syn*/*anti* contributions found in closely similar situations were used as an approximation in the calculation. Thus, the reported[17] values of the *syn*- and *anti*-contribution to 1-decene formation from the reaction of 1-decyltrimethylammonium chloride with potassium tert-butoxide in tert-butanol were used as the approximation in the corresponding reaction of 1-heptyltrimethylammonium salt (*II* → *IV*, R = H). As another example, the *syn*- and *anti*-contributions reported by Saunders[8] for the formation of *trans*-2 and *trans*-3-hexene from the reaction of 3-hexyltrimethylammonium salt with potassium tert-butoxide in tert-butanol we used, as the ap-

TABLE X

Contributions of the *syn*- and *anti*-Mechanism to *trans*-Alkene Formation in the Reaction of the Alkyltrimethylammonium Chlorides *I*, $RCH_2CH\overset{(+)}{[N(CH_3)_3}\overset{(-)}{Cl}].C_5H_{11}$, with Potassium tert-Butoxide in tert-Butanol and with Potassium Methoxide in Methanol (figures in parentheses): Selected Approximate Values

R	% *syn*[a] in the *trans*-Alkene Formation	
	$RCH_2CH{=}CHC_4H_9$ (*III*)	$RCH{=}CHC_5H_{11}$ (*IV*)
H	15[b] (≦5)[c]	— —
CH_3	80[d] (20)[e]	70[f] (10)[g]
C_2H_5	89[h] (24)[h]	80[d] (20)[g]
n-C_3H_7	89[i] (24)[i]	89[h] (24)[h]
i-C_3H_7	94[j] (57)[j]	90[j] (57)[j]
t-C_4H_9	99[k] (89)[k]	≧90[k] (≧90)[k]

[a] % *syn* + % *anti* = 100. [b] The value for *trans*-2-hexene formation from reaction of 2-hexyltrimethylammonium salt with tert-C_4H_9OK/tert-C_4H_9OH; ref.[8]. [c] Absence of *syn*-pathway was reported in the formation of *trans*-2-hexene from reaction of 2-hexyltrimethylammonium salt with n-C_4H_9OK/n-C_4H_9OH; ref.[8]. However, less than 5% contribution of the *syn*-mechanism would not be detected by the procedure employed. [d] The value for *trans*-3-hexene formation from reaction of 3-hexyltrimethylammonium salt with tert-C_4H_9OK/tert-C_4H_9OH; ref.[8]. [e] The value for *trans*-3-hexene formation from reaction of 3-hexyltrimethyl salt with CH_3OK/CH_3OH; ref.[8]. [f] The value for *trans*-2-hexene formation from reaction of 3-hexyltrimethylammonium salt with tert-$C_5H_{11}OK$/tert-$C_5H_{11}OH$; ref.[8]. [g] The value for *trans*-2-hexene formation from reaction of 3-hexyltrimethylammonium salt with n-C_4H_9OK/n-C_4H_9OH; ref.[8]. [h] The value for *trans*-5-decene formation from reaction of 5-decyltrimethylammonium salt with the base/solvent combination indicated; ref.[11]. [i] The experimental value; ref.[11]. [j] The average of the figures used for the higher and the lower homologous alkene (R = t-C_4H_9 and R = n-C_3H_7, respectively). [k] The experimental value; ref.[12].

proximation for the formation of *trans*-2 and *trans*-3-octene, respectively, in the corresponding reaction of 3-octyltrimethylammonium salt (*I* → *trans-IV* and *trans-III*, respectively, R = CH_3).

A closer consideration of the previously observed relationship[8,9,12,17] between alkyl substituents and *syn*/*anti* proportions in several base–solvent combinations allows us to expect that the error involved in such approximations does not exceed a 100% limit of inaccuracy in evaluation of the individual k^{syn} and k^{anti} rate constants. In a few instances, admittedly, the approximation was less straightforward (*cf.* footnotes *f* and *j* in Table X); however, even in such cases the uncertainty involved cannot affect validity of the conclusions to be drawn.

In general, the problem of mechanistic dissection concerns mainly *trans*-alkenes. In *cis*-alkene formation, the contribution of *syn*-pathway is known[8,9,11,12] to be generally very low. Accordingly, in the formation of *cis*-alkenes from the series *I* and *II* the *syn*-contribution was disregarded, in both the base–solvent combinations, the entire process being ascribed to the *anti*-pathway.

TABLE XI

Contributions of the *syn*- and *anti*-Mechanism to *trans*-Alkene Formation in the Reaction of Alkyltrimethylammonium Chlorides *II*, $RCH\overset{(+)}{[}N(CH_3)_3\overset{(-)}{Cl}]CH_2C_5H_{11}$, with Potassium Tert-Butoxide in Tert-Butanol and with Potassium Methoxide in Methanol (figures in parentheses): Selected Approximate Values

R	% *syn*[a] in the *trans*-Alkene Formation	
	$RCH{=}CHC_5H_{11}$ (*IV*)	$R^1R^2C{=}CHC_6H_{13}$ (*V*)
H	7·5[b] (−)[c]	— —
CH_3	15[d] (≦5)[e]	−[c] (−)[c]
C_2H_5	80[f] (20)[g]	70[h] (10)[i]
n-C_3H_7	89[j] (24)[j]	80[f] (20)[g]
i-C_3H_7	93[k] (54)[k]	22[l] (3)[l]
t-C_4H_9	97[m] (83)[m]	— —

[a] % *syn* + % *anti* = 100. [b] The value for 1-decene formation from reaction of 1-decyltrimethylammonium chloride with tert-C_4H_9OK/tert-C_4H_9OH; ref.[17]. [c] No reliable estimation can be done on basis of available data. [d] The value for *trans*-2-hexene formation from reaction of 2-hexyltrimethylammonium salt with tert-C_4H_9OK/tert-C_4H_9OH; ref.[8]. [e] See footnote *c* in Table X. [f] The value for *trans*-3-hexene formation from reaction of 3-hexyltrimethylammonium salt with tert-C_4H_9OK/tert-C_4H_9OH; ref.[8]. [g] The value for *trans*-3-hexene formation from reaction of 3-hexyltrimethylammonium salt with CH_3OK/CH_3OH; ref.[8]. [h] The value for *trans*-2-hexene formation from reaction of 3-hexyltrimethylammonium salt with tert-$C_5H_{11}OK$/tert-$C_5H_{11}OH$; ref.[8]. [i] The value for *trans*-2-hexene formation from reaction of 3-hexyltrimethylammonium salt with n-C_4H_9OK/n-C_4H_9OH; ref.[8]. [j] The value for *trans*-5-decene formation from reaction of 5-decyltrimethylammonium salt in the base/solvent combination indicated; ref.[11]. [k] The average of the figures used for the higher and the lower homologous alkene (R = t-C_4H_9 and R = n-C_3H_7, respectively). [l] The average from the values for 5-methyl-5-decene formation reported in the reaction of *erythro*- and *threo*-5-methyl-6-decyltrimethylammonium salt in the base/solvent combination indicated; ref.[10]. [m] The experimental value; ref.[12].

Control experiments: Stability of products was checked gas-chromatographically. In all the elimination runs examined, the ratios of the individual olefin-isomers did not change with time. In complementary experiments, a mixture containing internal standard, alkyldimethylamine and *cis*-alkenes (thermodynamically less stable isomers) was heated with the alkoxide solution under the conditions of the elimination run. No change in composition took place.

Gas chromatography: The measurements were performed on a Carlo Erba Fractovap GT chromatograph equipped with digital integrator. The alkyldimethylamines were analysed on an Apiezone/Chromosorb column (the support was pre-treated with 1M-KOH) at 150°C. The alkenes were analysed as reported elsewhere[13,18]. The reference alkenes were available from the previous work[13].

RESULTS

The approximate second-order rate constants of the main elimination pathways (*anti*- and *syn*-) participating in the reaction of the alkyltrimethylammonium salts *I* and *II* with 0·43M potassium tert-butoxide in tert-butanol at 35°C are summarized in Tables XII and XIII, respectively. The corresponding rate data from the reaction with 2·02M potassium methoxide in methanol at 115°C are given in Tables XIV and XV.

Pronounced differences between the pathways which proceed in the direction "away" and "towards" the substituent R can be seen from these rate data, in both the base–solvent combinations examined. At the same time, striking differences between the complementary *anti*- and *syn*-pathways are immediately apparent.

TABLE XII

Rate Constants (in l mol^{-1} s^{-1}) of the *syn*- and *anti*-Pathways in E2 Reaction of Alkyltrimethylammonium Chlorides *I*, $RCH_2\overset{(+)}{C}H[\overset{(-)}{N}(CH_3)_3Cl].C_5H_{11}$, with 0·43M Potassium Tert-Butoxide in Tert-Butanol at 35°C

R	$RCH_2CH{=}CHC_4H_9$ (*III*)			$RCH{=}CHC_5H_{11}$ (*IV*)		
	$10^7 k_{t\to t-III}^{syn}$	$10^7 k_{t\to t-III}^{anti}$	$10^7 k_{t\to c-III}^{anti}$	$10^7 k_{t\to t-IV}^{syn}$	$10^7 k_{t\to t-IV}^{anti}$	$10^7 k_{t\to c-IV}^{anti}$
H	1·2	6·9	32·4		(4 010)[a]	
CH_3	63·8	15·9	27·2	98·0	42·0	198·0
C_2H_5	74·6	9·2	24·8	73·3	18·3	28·8
n-C_3H_7	85·8	10·6	35·6	85·8	10·6	35·6
i-C_3H_7	141·4	9·0	34·1	27·0	3·0	1·5
t-C_4H_9	427·4	4·3	7·6	9·3	≦1·0	0·05

[a] The overall rate constant of 1-heptene formation (*syn* + *anti*).

TABLE XIII

Rate Constants (in l mol^{-1} s^{-1}) of the *syn*- and *anti*-Pathways in E2 Reaction of Alkyltrimethylammonium Chlorides *II*, $RCH[\overset{(+)}{N}(CH_3)_3\overset{(-)}{Cl}].CH_2C_5H_{11}$, with 0·43M Potassium Tert-Butoxide in Tert-Butanol at 35°C

R	$RCH{=}CHC_5H_{11}$ (*IV*)			$R^1R^2C{=}CHC_6H_{13}$ (*V*)		
	$10^7k_{II\to t-IV}^{syn}$	$10^7k_{II\to t-IV}^{anti}$	$10^7k_{II\to c-IV}^{anti}$	$10^7k_{II\to t-V}^{syn}$	$10^7k_{II\to t-V}^{anti}$	$10^7k_{II\to c-V}^{anti}$
H	1·9[a]	24·6[b]	24·6[b]	—	—	—
CH_3	2·2	12·2	57·6		(4 708)[c]	
C_2H_5	62·6	15·6	28·3	99·0	42·4	187·0
n-C_3H_7	80·8	10·0	26·8	79·3	19·8	31·3
i-C_3H_7	164·6	12·4	3·6	9·6[d]	33·8[e]	33·8[e]
t-C_4H_9	171·1	5·3	6·6	—	—	—

[a] The rate constant of the *syn*-pathway in 1-heptene formation divided by the statistical factor 2. [b] The rate constant of the *anti*-pathway in 1-heptene formation divided by the statistical factor 2. [c] The overall rate constant of 1-octene formation (*syn* + *anti*). [d] The rate constant of the *syn*-pathway in the trisubstituted olefin formation ($R^1 = R^2 = CH_3$). [e] The rate constant of the *anti*-pathway in the trisubstituted olefin formation ($R^1 = R^2 = CH_3$).

TABLE XIV

Rate Constants (in l mol^{-1} s^{-1}) of the *syn*- and *anti*-Pathways in E2 Reaction of Alkyltrimethylammonium Chlorides *I*, $RCH_2CH[\overset{(+)}{N}(CH_3)_3\overset{(-)}{Cl}].C_5H_{11}$, with 2·02M Potassium Methoxide in Methanol at 115°C

R	$RCH_2CH{=}CHC_4H_9$ (*III*)			$RCH{=}CHC_5H_{11}$ (*IV*)		
	$10^7k_{I\to t-III}^{syn}$	$10^7k_{I\to t-III}^{anti}$	$10^7k_{I\to c-III}^{anti}$	$10^7k_{I\to t-IV}^{syn}$	$10^7k_{I\to t-IV}^{anti}$	$10^7k_{I\to c-IV}^{anti}$
H	≦0·5	10·0	31·0		(774)[a]	
CH_3	3·1	12·2	53·9	5·7	51·5	164·0
C_2H_5	3·4	10·9	59·4	3·3	13·1	64·8
n-C_3H_7	3·4	10·5	57·1	3·4	10·5	57·1
i-C_3H_7	9·8	7·4	60·8	6·2	4·6	11·2
t-C_4H_9	21·7	2·7	33·2	~3·1	≦0·3	0·6

[a] The overall (*syn* + *anti*) rate constant of 1-heptene formation.

A near-independence of rates on the substituent R is found, both in the series *I* and *II*, for the *anti*-pathways which proceed "away" from the variable group ($k^{anti}_{I\to t-III}$, $k^{anti}_{I\to c-III}$ and also $k^{anti}_{II\to t-IV}$, $k^{anti}_{II\to c-IV}$). This contrasts with a gradual, and very pronounced, increase of elimination rates with increasing complexity of R ($H < CH_3 < C_2H_5 \leqq$ n-C_3H_7 < i-C_3H_7 < t-C_4H_9) observed in the complementary *syn*-pathways ($k^{syn}_{I\to t-III}$ and also $k^{syn}_{II\to t-IV}$).

On the other hand, a sharp decrease of rates with the increasing complexity of R is found in the *anti*-pathways which proceed "towards" the variable group ($k^{anti}_{I\to t-IV}$, $k^{anti}_{I\to c-IV}$ and also $k^{anti}_{II\to t-V}$ and $k^{anti}_{II\to c-V}$). This now contrasts with a mild decrease (in tert-C_4H_9OK–tert-C_4H_9OH) or even (in CH_3OK—CH_3OH) with a near-independence of rates on R found in the concurring *syn*-pathways ($k^{syn}_{I\to t-IV}$ and $k^{syn}_{II\to t-V}$).

As a further inspection of the rate trends shows, the alkyl effects observed in both the base–solvent systems are in most cases rather similar. For sake of simplicity, we shall therefore discuss first the general feature of the alkyl effects on basis of the rate data obtained in the reaction with tert-C_4H_9OK in tert-C_4H_9OH. Thereafter, we shall comment on the differences observed on going to the other (CH_3OK–CH_3OH) base–solvent system.

TABLE XV

Rate Constants (in l mol^{-1} s^{-1}) of the *syn*- and *anti*-Pathways in E2 Reaction of Alkyltrimethylammonium Chlorides *II*, $RCH\overset{(+)}{[N(CH_3)_3}\overset{(-)}{Cl}].CH_2C_5H_{11}$, with 2·02M Potassium Methoxide in Methanol at 115°C

R	RCH=CHC_5H_{11} (*IV*)			R^1R^2C=CHC_6H_{13} (*V*)		
	$10^7k^{syn}_{II\to t-IV}$	$10^7k^{anti}_{II\to t-IV}$	$10^7k^{anti}_{II\to c-IV}$	$10^7k^{syn}_{II\to t-V}$	$10^7k^{anti}_{II\to t-V}$	$10^7k^{anti}_{II\to c-V}$
H		(17)[a]		—	—	—
CH_3	≦0·5	10·8	34·1		(827)[b]	
C_2H_5	3·2	13·0	51·8	5·5	49·3	154·0
n-C_3H_7	3·5	11·1	58·8	2·9	11·8	58·8
i-C_3H_7	28·1	23·9	14·4	5·3[c]	172·3[d]	172·3[d]
t-C_4H_9	29·4	6·0	47·6	—	—	—

[a] The overall (*syn* + *anti*) rate constant of 1-heptene formation. [b] The overall (*syn* + *anti*) rate constant of 1-octene formation. [c] The rate constant of the *syn*-pathway in the trisubstituted ($R^1 = R^2 = CH_3$) olefin formation. [d] The rate constant of the *anti*-pathway in the trisubstituted ($R^1 = R^2 = CH_3$) olefin formation.

DISCUSSION

No causal understanding of alkyl-substituent effects in bimolecular elimination can be attained, at least on basis of present knowledge, unless a distinction is made between the contributing steric and polar components. Ingold in his fundamental study of E2 reactions suggested[3] that such a distinction can be made, simply, by determining the rate pattern of elimination in appropriate homologous series, the argument being that a steric effect, once it starts, builds-up very rapidly and therefore "telescopes", whereas polar effects exhibit a monotonous (additive) form of variation. Examining overall elimination rates from several homologous series of alkyltrimethylammonium salt (similar to *I* and *II*) on these grounds, Ingold with his colleagues reached to the generalizing conclusion: "The inductive and electromeric effects dominate the picture of eliminations down to the simplest example of Hofmann and Saytzeff. These two polar effects belong to that picture in principle, creating its familiar kinetic and orientational pattern. Steric hindrance is inessential to that pattern. It enters as a complication, in certain critical situations above determinable thresholds of structural complexity ... It is not a viable idea to replace the inductive effect by the steric effect in explanation of the kinetic and orientational pattern of elimination as a whole".

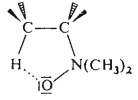
Recent development, however, cast some doubts on this often quoted statement. The *syn-anti* dichotomous course poses, as we already pointed out in the Introductory part, the most obvious objection. At the same time, another – and in our opinion equally serious – objection can be raised on basis of the accumulating evidence[13,19,20] which shows that steric and polar effects of alkyl groups are not always different functions of structure, contrary of the Ingold's basic assumption.

Very pertinently to the present problem, we observed earlier in a related study of amine oxide decomposition[13] (Cope elimination) that the elimination rates exhibit in the homologous series *I* and *II* ($X = N(CH_3)_2O$) additive form of variation, although the responsible alkyl effect is – as a detailed examination revealed – of a steric, not of a polar origin. It shows that a simple determination of rate pattern in homologous elimination series, alone, does not suffice for an unambiguous distinction between steric and polar effects of alkyl group.* Additional criteria will be therefore applied in the present discussion.

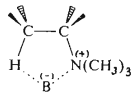
* A concomitant observation that an excellent linear fit exists in the Cope elimination of the amine oxides *I* and *II* between log *k* and σ^* constants for R similarly shows that also Taft's empirical parameters are only of an illusory diagnostic value.

Alkyl Effects in syn-*Elimination*

It is useful to compare the rate data for *syn*-elimination from the E2 reaction of alkyltrimethylammonium salts we now have under study with those data which we reported earlier[13] for the Cope elimination of the corresponding amine oxides *I* and *II* ($X = N(CH_3)_2O$). It is assumed that both the two compared reactions require a nearly *syn*-periplanar arrangements of the bonds to be broken in the transition state (Scheme 2). Moreover, steric requirements of the dimethylamine oxide and trimethylammonium leaving groups are similar. Accordingly, steric effects of alkyl



A



B

SCHEME 2

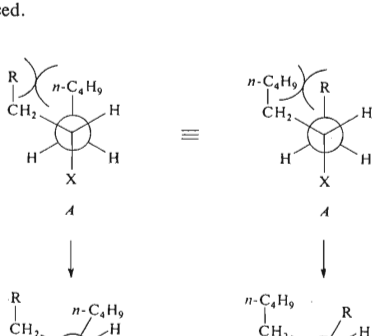
group in the two compared reactions should be also similar. On the other hand, polar effects of alkyl group need not to be similar in the amine oxide and in the trimethylammonium series. It is known[13,21] that the Cope elimination is insensitive towards polar effects: in the amine oxide series *I* and *II* the polar influence of R (inductive and electromeric) was shown[13] to be practically absent in the reaction. This circumstance, obviously, makes the amine oxide elimination a very convenient reference reaction for elucidation of alkyl effects in the corresponding alkyltrimethylammonium series where, owing to the presence of charges[3], polar effects are expected to be more important.

Steric effects: Let us examine first the *syn*-pathways in the Cope and in the Hofmann series *I* ($X = N(CH_3)_2O$ and $X = \overset{(+)}{N}(CH_3)_3\overset{(-)}{Cl}$, respectively) which proceed "away" from R and lead to *trans-III* alkene formation. In this particular process, the variable R group is always insulated from reaction centre by a methylene unit (Scheme 1); accordingly, polar influence of R on rate cannot be either in the Cope or in the Hofmann series significant.

As Fig. 1*a* shows, the dependence of rate on R ("rate profile") in the two compared pathways is remarkably similar. A very sharp increase of rate occurs on going from $R = H$ to $R = CH_3$, followed by a milder increase induced by lengthening and, further on, by branching the variable group. In the Cope as well as in the Hofmann series the rate constants of the slowest ($R = H$) and the fastest ($R = tert\text{-}C_4H_9$) homologue differ always by an impressive factor of about 400.

A very simple conformational explanation can be provided for this alkyl effect when extreme steric requirements of the dimethylamine oxide as well as trimethylammo-

nium leaving group are taken into account. As examination of models (Scheme 3) suggests, in accord with the earlier arguments[8,9,22], either of the two very bulky groups forces the adjacent alkyls on C_α and C_β as far away from itself as possible, into position where not only 1,2-synclinal but also 1,3-synperiplanar interactions between the alkyls by necessity take place (*A*). In spite of this energy minimization steric strain therefore has to exist in the amine oxides as well as in the quaternary salts, in dependence on bulk of R. When R = H, the strain is only small, however, it increases, very substantially, already on replacing the hydrogen by the methyl group (R = CH_3) because a severe 1,3-synperiplanar interaction between two alkyl groups is introduced.



SCHEME 3

Significantly, however, it is also seen from the Scheme that the repulsion between the alkyls can be diminished on going from the staggered conformation *A* to the eclipsed arrangements *B* or *C* which are required in the transition state for *syn*-elimination (*I* → *trans-III* and *I* → *trans-IV*, respectively). Accordingly, the accelerating effect of R which we found in the *I* → *trans-III* *syn*-pathways of both the two compared series can be taken to result from a relief of the ground-state strain. The circumstance that the greatest increase of rate occurs, both in the Cope and in the Hofmann series, on going from R = H to R = CH_3 lends an additional support to this conformational proposal.

Polar effects: As a simple consideration of Scheme 3 suggests, the alternative reactive arrangements for *syn*-elimination "away" and "towards" R (*B* and *C*,

respectively) are energetically similar. A resemblance between rate profiles for *syn*-elimination $I \rightarrow$ *t-III* and $I \rightarrow$ *t-IV* should be therefore found, in the Cope as well as in the Hofmann series *I*, provided that relief of ground-state strain is the main factor which controls rates in both the two directions. In a perfect accord with this assumption, a near-identity of the rate profiles $I \rightarrow$ *trans-III* and $I \rightarrow$ *trans-IV* is actually found in the amine oxide series *I* (Fig. 1*a* and 1*b*, respectively; full circles) indicating that the ground-state strain is indeed the main, or perhaps the sole, factor in the intramolecular reaction. Contrary to this assumption, however, a complete dissimilarity between the two corresponding rate profiles is found in the *syn*-elimination of the quaternary salts *I* (Fig. 1*a* and 1*b*, respectively; empty circles). A gradual decrease of rates with increasing bulk of R which is found in the Hofmann series for the $I \rightarrow$ $\rightarrow$ *trans-IV syn*-pathway strongly suggests that another effect now takes part in the reaction and overweights the effect resulting from the ground-state strain.

A very reasonable explanation for this adverse effect and at the same time for the difference between the Cope and the Hofmann series *I* (Fig. 1*b*) can be given in polar terms. It was suggested by Ingold[3] that alkyl substituent attached to C_β is capable to exert an electron-releasing effect which by decreasing the C_β—H bond acidity slows-down elimination rates in the order H > CH_3 > C_2H_5 > n-C_3H_7 > i-C_3H_7 > tert-C_4H_9, in accord with the observed trend. Significantly, the inductive effect is not expected[3] to operate generally in 1,2-eliminations but only when a large

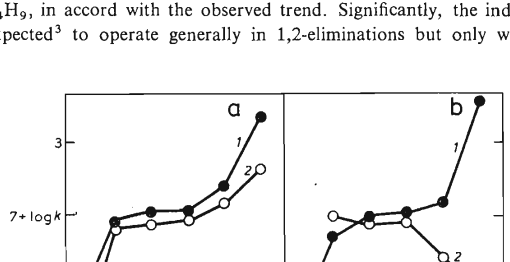


FIG. 1

Effect of Alkyl Substituent, R, on Rates of *syn*-Elimination in the Homologous Series *I*

X = $\overset{(+)}{N}(CH_3)_3Cl^{(-)}$: in tert-$C_4H_9OK$–tert-$C_4H_9OH$ at 35°C, X = $N(CH_3)_2O$: in tert-C_4H_9OK – –tert-C_4H_9OH at 70°C; taken from ref.[13].

a: $I \rightarrow$ *trans III*; *1* = NMe_2O; *2* X = $\overset{(+)}{N}Me_3$; *b*: $I \rightarrow$ *trans-IV*; *1* = NMe_2O, *2* X = $\overset{(+)}{N}Me_3$.

degree of negative charge is developed on the carbon C_β in the transition state (paenecarbanion region[23] in the spectrum of transition states). All available evidence[23,24] suggests that alkyltrimethylammonium salts eliminate usually in the paenecarbanion region, the *syn*-pathway being probably closer[10,15] to the carbanion extreme than the *anti*-elimination component. In the amine oxide elimination, on the other hand, no significant charge development was noted[13,21] in the transition state. It suggests that Cope elimination is a highly concerted process. Eventually, it represents a homolytic rather than a heterolytic reaction.

Inessentiality of base-approach hindrance: A steric alternative to the aforementioned polar effect has to be also considered. It was suggested already by Brown in the dispute[2,25] with the polar school that repulsion between the bulky tert-butoxide base and alkyl placed on C_β may give rise to base-approach hindrance and in this way slows-down the elimination rates. The original suggestion was given for *anti*-elimination; however, as a simple consideration may show, the hindrance should be – other things being equal – the same in the corresponding *anti*- and *syn*-pathways. Accordingly, the slowing-down of the $I \rightarrow$ *trans-IV syn*-pathway with increasing bulk of R which we observe in the Hofmann but not in the Cope elimination series could result also from the hindrance to approach of the external bulky base.

In order to decide whether steric hindrance of this type can play an essential role, we have to rely upon the results obtained in less ambiguous E2 series in which inductive effect of R is only small. Recently[16], we have investigated *anti*-elimination of open-chain tosylates with dissociated tert-butoxide base in the same homologous series (*I*; X = OTs). We have found in the tosyloxy series that the values of $k_{I\rightarrow t-III} : k_{I\rightarrow t-IV}$ are always rather close to unity, irrespective of the bulk of R. It strongly suggests that steric hindrance to the tert-butoxide base approach by R_β is not essential, at least on the level of steric complexity which can be attained in homologous series *I*.

Alkyl effects at a higher level of structural complexity: In the homologous series of alkyltrimethylammonium salts *I* we investigated the effect of alkyl substituent which was placed β in respect to the leaving group. The positionally isomeric series *II* allows us to compare the corresponding effect of the alkyl which is placed in sterically more exposed α position.

As a comparison of Tables XII and XIII shows, a marked resemblance exists between the corresponding rate profiles in the two isomeric series, lending thus a further significance to our previous conclusions. Evidently, the ground-state strain which we proposed for the acceleration in the $I \rightarrow$ *t-III syn*-pathway accounts also for the similar trend found in the $II \rightarrow$ *t-IV syn*-pathway proceeding also "away" from R group. The inductive effect of R probably accounts, on the other hand, for the retardation which is observed in both the corresponding *syn*-pathways which proceed "towards" the alkyl group ($I \rightarrow$ *t-IV* and $II \rightarrow$ *t-V*, respectively).

Alkyl Effects in anti-*Elimination*

In discussion of the *anti*-pathways participating in the elimination of the quaternary salts *I* and *II* the complementary *syn*-pathways can now serve as reference reactions. The ground-state conformation is the same for the competing *anti*- and *syn*-pathways; accordingly, the differences observed between the corresponding *anti*- and *syn*-rate profiles reflect only the differences between the alternative transition states.

Steric effects: The rate profiles for the *anti*- and *syn*-pathway $I \rightarrow$ *trans-III*, and at the same time for the *anti*-pathway $I \rightarrow$ *cis-III* (all assumedly unaffected by the polar influence of R), are compared in Fig. 2*a*. It is immediately seen that the rates of both the two *anti*-pathways ($I \rightarrow$ *trans-III* and $I \rightarrow$ *cis-III*) are practically independention R (except for a mild decrease found in the extreme homologue; R = tert-C_4H_9), at variance with the situation which we observed in the complementary *syn*-pathway. As we suggested, the upward trend in the rate profile for the $I \rightarrow$ *t-III syn*-pathway originates from a relief of ground-state strain. Accordingly, we have now to ask what happens with this strain in the concurring *anti*-pathways.

As it follows from Scheme 4, the repulsive interaction between R group and n-butyl group which is mainly responsible for the strain in the ground-state conformation *A* persists also in the reactive arrangement *B* which leads to *cis-III* alkene formation.

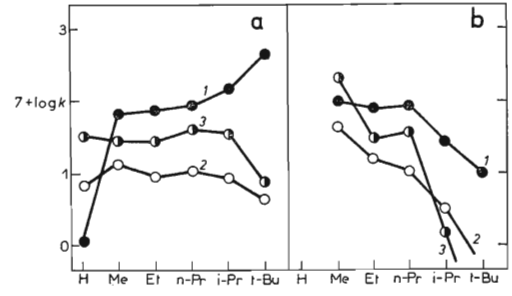


FIG. 2

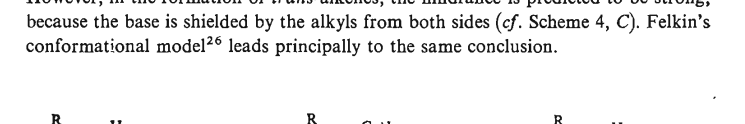
Effect of Alkyl Substituent, R, on Rates of the Competing *anti*- and *syn*-Pathways in the E2 Reaction of Quaternary Salts *I* ($X = \overset{(+)}{N}(CH_3)_3\overset{(-)}{Cl}$) with Potassium tert-Butoxide in tert-Butanol at 35°C

a: $I \rightarrow$ *III*; *1 syn* $\rightarrow$ *trans-III*; *2 anti* $\rightarrow$ *trans-III*; *3 anti* $\rightarrow$ *cis-III*; *b*: $I \rightarrow$ *IV*; *1 syn* $\rightarrow$ *trans-IV*, *2 anti* $\rightarrow$ *trans-IV*; *3 anti* $\rightarrow$ *cis-IV*.

The independence of rate on R which we observe in the $I \rightarrow$ *cis-III anti*-pathway can be therefore explained simply by perseverance of the original strain.

On the other hand, the conformational situation concerning the $I \rightarrow$ *trans-III anti*-pathway is by no means so straightforward. Now, as Scheme 4 suggests, the starting interaction between n-butyl and R group in *A* is replaced by a constant gauche interaction between n-butyl and trimethylammonium group in *C*. It follows that only the strain in *A* increases with R whereas the strain in *C* is essentially constant in the whole series. Consequently, the energy difference between ground state and transition state for the $I \rightarrow$ *t-III anti*-pathway should diminish gradually with increasing bulk of R. Accordingly, a gradual increase of rate with R, such as is observed in the $I \rightarrow$ *t-III syn*-pathway, should be found also in the complementary *anti*-pathway, contrary to Fig. 2*a*.

In order to resolve the apparent conflict between this conformational analysis and the elimination rates, the buttressing effect of the leaving group on base-approach hindrance must be also taken into account. As it follows from Scheme 3, the trimethylammonio group, by forcing the alkyls on C_α and C_β as far away from itself as possible, opens, in actual fact, a free access of base to β-hydrogen in the *syn*-elimination pathways. In the *anti*-pathways, however, the buttressing may lead to an adverse result. It was suggested already by Saunders[8] and also by Felkin[26] that the trimethylammonio group enforces such an arrangement of adjacent alkyl groups in *anti*-elimination, in which the alkyls can selectively shield base approach. According to Saunders[8], the shielding is only minor in the formation of *cis*-alkenes, because the approaching base is shielded only from one side (*cf.* Scheme 4, *B*). However, in the formation of *trans*-alkenes, the hindrance is predicted to be strong, because the base is shielded by the alkyls from both sides (*cf.* Scheme 4, *C*). Felkin's conformational model[26] leads principally to the same conclusion.



SCHEME 4

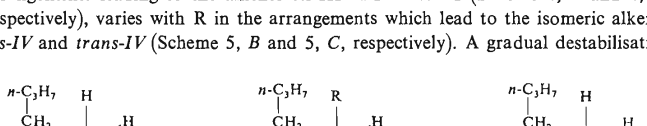
In this way, it appears justified to suggest that two steric factors – relief of ground-state strain and hindrance to base approach – are simultaneously involved in the $I \rightarrow$ *t-III anti*-path. We assume that superposition of the two interrelated factors

which individually may be very strong leads always to kinetic results more or less independent on R because, obviously, the two factors are opposite functions of R.

Significantly, a quite analogous situation is found also in the positionally isomeric series *II* (Table XIII), the rates of the *II* → *cis-IV* as well as of the *II* → *trans-IV* *anti*-pathways being again almost independent on R, in a full accord with the present suggestions.

Polar effects: Contrary to the rates of the above *anti*-pathways *I* → *cis-III* and *I* → *trans-III* (Fig. 2*a*), a very pronounced decrease of rates with increasing complexity of R is found in both the corresponding *anti*-pathways *I* → *cis-IV* and *I* → *trans-IV* which proceed "towards" the group R (Fig. 2*b*).

It would be tempting to attribute this difference mainly to the inductive effect of R, in analogy with the conclusion we have already reached for the complementary *syn*-paths. However, operation of steric effects cannot be dismissed in the present case. Namely, it is seen from comparison of the Schemes 4 and 5 that the synclinal interaction between alkyl and trimethylammonio group, which is constant in the arrangements leading to the alkenes *cis-III* and *trans-III* (Scheme 4, *B* and 4, *C*, respectively), varies with R in the arrangements which lead to the isomeric alkenes *cis-IV* and *trans-IV* (Scheme 5, *B* and 5, *C*, respectively). A gradual destabilisation



SCHEME 5

of 5*B* relative to 4*B*, and of 5*C* relative to 4*C*, which thus results on increasing bulk of R presumably contributes to the decrease of rates observed in the *I* → *cis-IV* as well as *I* → *trans-IV* *anti*-paths.

Independence of Alkyl Effects on Base–Solvent System

In order to see whether alkyl effects in the complex E2 reaction of the quaternary salts *I* and *II* depend much on the nature of base–solvent system, we compare the individual rate profiles from the reaction induced by tert-C_4H_9OK-tert-C_4H_9OH (Tables XII and XIII) with those which we obtained in the corresponding reaction induced by CH_3OK–CH_3OH (Table XIV and XV).

As the comparison shows, the corresponding rate profiles are in most instances remarkably similar, suggesting that alkyl effects in the two base–solvent systems are

very much the same. The only marked difference which can be found between the two base–solvent systems concerns the *syn*-pathways which proceeds "towards" the R group (*I* → *trans-IV* and also *II* → *trans-V*). In tert-C_4H_9OH–tert-C_4H_9OH, a gradual decrease of rates occurs in both the two *syn*-pathways in the order CH_3 > > C_2H_5 ≧ n-C_3H_7 > i-C_3H_7 > tert-C_4H_9 resulting, as we already pointed out, from a prevalence of the inductive effect of the R group over the relief of ground-state strain. In contrast, a near-independence of rates on R is found for the two *syn*-pathways in the reaction performed in CH_3OK–CH_3OH. In our opinion, this indicates only a more balanced operation of the two opposing effects in the latter reaction.

Alkyl Effects in the Competing S_N2 *Reaction*

It is appropriate to comment also on the rates of the concurring S_N2 process which in the alkyltrimethylammonio series *I* and *II* leads to the formation of corresponding alkyldimethylamines (*I* or *II*, X = $N(CH_3)_2$) and represents; in most instances, a considerable part of the overall reaction (Tables II–V). As Tables VI and VII (and also Tables VIII and IX) show, the rates of the S_N2 process increase with increasing bulk of R resembling thus the situation we discussed in connection with the *syn*-elimination pathways (*I* → *trans-III* and *II* → *trans-IV*). However, in contrast to the *syn*-elimination, the increase of rates in the S_N2 process is pronounced only for the most bulky groups (R = i-C_3H_7 and R = tert-C_4H_9) and, moreover, only in the series *II*: In the series *I* the substitution rates are almost unaffected by R.

A satisfactory explanation for the rate pattern of the demethylation reaction can be provided when solvation of the trimethylammonio group is taken into account. In the homologous series *I* the R group can be always placed *anti* in respect to the trimethylammonio group (Scheme 3, *A*). Accordingly, interference between the R group and solvent shell surrounding the trimethylammonio group can be easily avoided in the whole series *I*. In the positionally isomeric series *II*, on the other hand, the interference cannot be avoided when R is a branched group (R = i-C_3H_7 and, mainly, R = tert-C_4H_9). Under such circumstances a partial desolvation of the trimethylammonio group presumably occurs.

Recently, we have found[27] that such a hindrance to solvation occurs also in the corresponding dimethylamino series (*I* and *II*, X = $N(CH_3)_2$). Significantly, we have found at the same time that the hindrance affects rate of quaternisation in these series: a gradual disappearance of solvent shell around the basic group opens a more free access to the reaction site and tends thus to increase rate of quaternisation.

We assume that an analogous effect exists also in the reverse (demethylation) reaction. Accordingly, we propose that the acceleration found in the S_N2 reaction of the quaternary salts *II* (Tables VII and IX) results from steric hindrance to solvation of the trimethylammonio group.

In this way, the rate pattern which we have now found in the demethylation

reaction bears upon the recent Saunders' suggestion[28] that steric hindrance to solvation of trimethylammonio group rather than relief of ground-state strain controls rate of *syn*-elimination of open-chain quaternary salts. The present rate data for the accompanying S_N2 process clearly show that the threshold of steric complexity when the solvation of leaving group becomes hindered is very high. Accordingly, steric hindrance to solvation of the trimethylammonio group cannot explain satisfactorily the rate pattern for *syn*-elimination we found in the trimethylammonium series *I* and *II*.

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