# ALKYL STRUCTURE–SELECTIVITY RELATIONSHIPS IN E2 REACTIONS OF OPEN-CHAIN TOSYLATES: STERIC EFFECTS IN THE *anti*-PATHWAY INDUCED BY DISSOCIATED AND ASSOCIATED TERT-BUTOXIDE BASE*

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Received May 12th, 1977

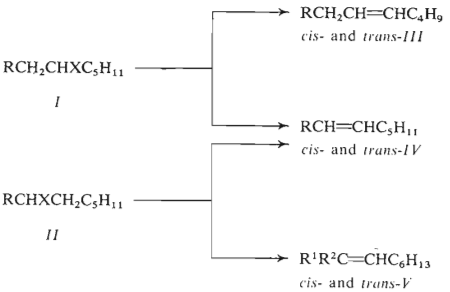
The effect of alkyl structure and base association on stereo- and regio-selectivity of *anti*-elimination was investigated in two homologous series of positionally-isomeric tosylates, $RCH_2CHOTs.C_5H_{11}$ (*I*) and $RCHOTsCH_2C_5H_{11}$ (*II*); R = H, $CH_3$, $C_2H_5$, n-$C_3H_7$, iso-$C_3H_7$ and tert-$C_4H_9$. Olefin-isomer distribution from overall reaction with the dissociated (in dimethylformamide) and associated (in tert-butanol) potassium tert-butoxide was determined in the two series *I* and *II* and it was corrected, where necessary, on operation of side elimination processes (*syn*-E2 and E1). Orientation patterns were thus obtained parallelly for the clean *anti*-pathways induced by the alternative base forms. Fundamental differences are found in the geometrical orientation of the two compared reactions. The dissociated base leads, with a single (and very remarkable), exception to the preferential *trans*-alkene formation. On the other hand, the associated base leads, again with a single exception, to the preferential *cis*-isomer formation. In striking contrast to the geometrical orientation, the positional orientation is almost identical in both the compared reactions. However, a complete reversal in the positional orientation is induced by variation of alkyl structure within the homologous series *I* and *II*. With aid of subsidiary experiments, a full explanation is provided for the observations by a separate analysis of alkyl–alkyl, alkyl–tosyloxy, alkyl–base and base–tosyloxy interactions. A resolution of current (controversial) views concerning steric effects in E2 reactions is further progressed on these grounds.

The role of steric effects in E2 reactions with metal alkoxides has been subject of lasting interest[1] and conflicting[2–4] views over past decades. Recent findings demonstrating dichotomy of stereochemical pathways[1,5–9] (*anti vs syn*) and also dichotomy of base forms[9–12] (dissociated *vs* associated) in the reaction added a new dimension to this controversial problem. In particular, the recent findings showed that a meaningful understanding of steric effects in the reaction can be attained only when individual stereochemical pathways, induced by homogeneous base forms, are separately examined.

With this objective, we have now analyzed E2 reaction of two homologous series of open chain tosylates, *I* and *II*, with the dissociated (in dimethylformamide),

* Part XXXVI in the series Elimination Reactions; Part XXXV: This Journal *42*, 2161 (1977).

and with the associated (in tert-butanol) form of potassium tert-butoxide (Scheme 1).




X = OTs
R = H, $CH_3$, $C_2H_5$, *n*-$C_3H_7$, *iso*-$C_3H_7$, *tert*-$C_4H_9$

SCHEME 1

Olefin-isomer distribution was quantitatively determined for all the tosylates *I* and *II* in the two reactions. On basis of previous evidence, approximate correction was made, where necessary, for the contribution of *syn*-pathway (and of solvolysis) to the formation of individual olefins. Geometrical and positional orientation was thus determined, parallelly, for the *anti*-pathway induced by the dissociated and by the associated tert-butoxide base. Steric effects resulting from alkyl–alkyl, alkyl–tosyloxy, alkyl–base and base–tosyloxy interactions in the two processes could be comfortably analysed on these grounds.

## EXPERIMENTAL

*Synthesis*: The tosylates *I* and *II* were prepared from the corresponding alcohols[5,6,13] by treating with *p*-toluenesulphonyl chloride in pyridine at 0°C. The time necessary for completion of the reaction varied between 0·5 h and 10 days, in dependence on the bulk of adjacent alkyls. Usual work-up afforded invariantly oily products in nearly quantitative yields. The tosylates were stored in a refrigerator and dried on the oil pump before use. The purity was checked by elemental analysis. 4-Chloro-2,2-dimethylnonane was prepared from the corresponding alcohol by the procedure described previously[9].

*Elimination runs*: 0·3—0·5 mmol of the tosylate was dissolved in appropriate alkoxide solution (three-fold excess) and heated in sealed tubes under nitrogen. The conditions are summarized in Table I. The contents were transferred into the volumetric flask (50 ml) containing saturated aqueous sodium chloride (20 ml) and pentane (1 ml). The flask was made up to mark with water.

thoroughly shaken and a sample of the pentane layer injected directly into the vapour-phase chromatograph.

*Vapour-phase chromatography*: The alkene mixtures were analyzed on the Carlo Erba Fractovap GT apparatus under conditions reported in a previous[14] paper. The reference alkenes were also available from the previous work[14]. Preparative separation of alkene mixtures (*vide infra*) was performed on the same apparatus using Apiezone/Chromosorb column.

*Stability of products*: Known mixtures of the alkenes *II*, *IV* and *V* (rich in less stable isomers) were heated with the alkoxide solutions under conditions of the elimination runs. No isomerization has taken place.

TABLE I
Conditions Employed in the Elimination Runs

| Base/Solvent | Molarity of base in mol/l | Temperature Time °C/*h* |
|---|---|---|
| tert-$C_4H_9OK$/tert-$C_4H_9OH$ | 0·45 | 110/10 |
| tert-$C_4H_9OK$/$HCON(CH_3)_2$ | 0·45 | 20/2 |
| $C_2H_5OK$/$C_2H_5OH$ | 1·0 | 120/10 |

## RESULTS AND DISCUSSION

Customarily, evidence on operation of steric effects is obtained from examination of olefin-isomer distribution (orientation pattern) in appropriate homologous series. However, as we already pointed out at several occassions[9,15,16], such evidence is warranted only when mechanistic homogeneity within the examined series is clearly established.

Accordingly, due precautions have to be taken also in examining the reaction of the tosylates *I* and *II* with potassium tert-butoxide in dimethylformamide and in tert-butanol. Before we enter discussion of steric effects in the two reactions, we summarize the available evidence indicating that the former reaction (in dimethylformamide) is induced prevalently by the dissociated t-butoxide anion, whereas the latter (in tert-butanol) by the associated base. Also, we summarize evidence that the former reaction represents, over the full spectrum of the alkyl structures examined, a uniform *anti*-elimination process. For the latter reaction, approximate correction will be made for participation of *syn*-E2 and E1-pathways. In this way, the orientation patterns for the *anti*-pathway induced by the dissociated and the associated tert-butoxide base will be obtained.

*Competition of base forms*: The participation of dissociated and associated form of potassium tert-butoxide in bimolecular elimination depends on solvent[9-12], overall base concentration[17] and also on substrate[9]. For unbranched open-chain tosylates, the recent evidence[9,11,12] showed that the dissociated base predominates (at 0·5M overall concentration) in dimethylformamide, whereas the associated form is (in comparable concentration region) the main reactive species in tert-butanol or in benzene. A complementary evidence will be presented (*vide infra*) that an analogous situation holds also for the branched tosylates.

anti *vs* syn *Competition*: The competition depends critically on alkyl structure[6], leaving group[9] as well as base-solvent combination[8,9,11,12]. Usually, a pronounced increase of the *syn*-contribution is found on increasing alkyl-structure[6,7] complexity of substrate. However, for the reaction of unbranched[5] (*I*; R = n-$C_3H_7$) as well as branched[6] (*I* and *II*; R = tert-$C_4H_9$) tosylates with potassium tert-butoxide in dimethylformamide we found that *cis*- and *trans*-alkenes were formed almost exclusively (>95%) by *anti*-elimination. We assume accordingly that within the series *I* and *II* the contribution of *syn*-pathway to the overall reaction is negligibly small.

For the reaction of tosylates *I* and *II* with potassium tert-butoxide in tert-butanol, the situation is more involved. Presumably, the *syn*-pathway can be neglected generally for the *cis*-alkene formation and also for the trisubstituted alkene (*V* from *II*; R = iso-$C_3H_7$). The supporting

TABLE II

*syn*-Contributions is E2 Reaction of Open-Chain Tosylates with Associated Tert-Butoxide Base: Reported Values

| Entry | *trans*-Alkene | Starting Tosylate | Conditions | % *syn*[a] | Ref. |
|---|---|---|---|---|---|
| *1* | *III*; R = n-$C_3H_7$ | *I*; R = n-$C_3H_7$ | tert-$C_4H_9OK$ (tert-$C_4H_9OH$) | 14·5 | 5 |
| *2* | *III*; R = n-$C_3H_7$ | *I*; R = n-$C_3H_7$ | tert-$C_4H_9OK$ ($C_6H_6$) | 29 | 5 |
| *3* | $CH_3CH{=}CHC_3H_7$ | $CH_3CHOTsC_4H_9$ | tert-$C_4H_9ONa$ (tert-$C_4H_9OH$) | 12 | 19 |
| *4* | $CH_3CH{=}CHC_3H_7$ | $C_2H_5CHOTsC_3H_7$ | tert-$C_4H_9ONa$ (tert-$C_4H_9OH$) | 16 | 19 |
| *5* | $C_2H_5CH{=}CHC_2H_5$ | $C_2H_5CHOTsCH_2C_2H_5$ | tert-$C_4H_9ONa$ (tert-$C_4H_9OH$) | 29 | 19 |
| *6* | *III*; R = tert-$C_4H_9$ | *I*; R = tert-$C_4H_9$ | tert-$C_4H_9OK$ ($C_6H_6$) | ~70 | 6 |
| *7* | *IV*; R = tert-$C_4H_9$ | *II*; R = tert-$C_4H_9$ | tert-$C_4H_9OK$ ($C_6H_6$) | ~70 | 6 |
| *8* | *IV*; R = tert-$C_4H_9$ | *I*; R = tert-$C_4H_9$ | tert-$C_4H_9OK$ ($C_6H_6$) | <10 | 6 |

[a] % *syn* + % *anti* = 100.

evidence follows from the pertinent results[5,6,18] we obtained for the tosylate *I*, R = n-$C_3H_7$; *I*, R = tert-$C_4H_9$; *II*; R = tert-$C_4H_9$ and for 5-methyl-6-decyl tosylate in the reaction with the associated base (in tert-butanol and/or in benzene). A great prevalence of *anti*-elimination (≧95%) in the formation of the aforementioned isomers was invariantly found.

The experimental evidence available for the formation of *trans*-alkenes by the associated base is summarized in Table II. About 15% *syn*-contribution to *trans*-5-decene formation (*III*; R = n-$C_3H_7$) from the tosylate *I*; R = n-$C_3H_7$ was found under the same conditions as we now employed in this study (entry *1*). For lower homologues (*trans*-2-hexene and *trans*-3-hexene; entry *3*—*5*), the *syn*-contribution determined[19] in sodium tert-butoxide–tert-butanol combination vary between 12—29%. It is known,[20] however, that sodium tert-butoxide is substantially more effective than potassium tert-butoxide in supporting the *syn*-pathway. This allows us to expect that the actual *syn*-contributions to the *trans*-alkene formation from the unbranched tosylates *I* and *II* (R = $CH_3$, $C_2H_5$, n-$C_3H_7$) in the present reaction do not exceed that which we found for *trans*-5-decene (entry *1*). For sake of simplicity, we propose to omit the minor contributions from the following discussion.

About 70% *syn*-contribution was found in the formation of the "double-branched" *trans*-alkenes *III* and *IV* arising respectively from the tosylates *I* and *II*, (R = tert-$C_4H_9$), in the reaction with the associated potassium tert-butoxide base in benzene (entry *6* and *7*, respectively). It is known[5,10] that *syn*/*anti* ratios are lower in tert-butanol than in benzene; an approximate recalculation will be made from comparison of the corresponding data in the entries *1* and *2*. The *syn*-contribution found for the "double-branched" *trans*-alkene *IV* from the reaction of the tosylate *I* is rather small (entry *8*) and it will be ignored. No experimental data are available for the formation of the isopropyl analogues (*trans-III* and *trans-IV*; R = iso-$C_3H_7$). Tentatively, we shall assume that *syn*-contributions to their formation are intermediate between those found for the corresponding lower (R = n-$C_3H_7$) and higher (R = tert-$C_4H_9$) homologues.

Accordingly, major contributions of *syn*-pathway to the reaction of tosylates *I* and *II* with potassium tert-butoxide in tert-butanol are estimated as indicated in Table III.

E2 *vs* E1 *competition*: In the reaction of the tosylate *II*; R = tert-$C_4H_9$ with potassium tert-butoxide in tert-butanol we found, aside from the expected four olefin isomers (Scheme 1), two additional products *A* and *B*. The proportion of both *A* and *B* increased gradually on lowering the base concentration and reached maximum (50%) under solvolytic conditions (tert-butanol

TABLE III

Major Contributions of *syn*-Pathway in the Reaction of Tosylates *I* and *II* with Potassium Tert-Butoxide in Tert-Butanol: Estimated Values

| *trans*-Alkene | Starting tosylate | % *syn* in overall E2[a] |
|---|---|---|
| *III*; R = iso-$C_3H_7$ | *I*; R = iso-$C_3H_7$ | 30 |
| *III*; R = tert-$C_4H_9$ | *I*; R = tert-$C_4H_9$ | 50 |
| *IV*; R = iso-$C_3H_7$ | *II*; R = iso-$C_3H_7$ | 30 |
| *IV*; R = tert-$C_4H_9$ | *II*; R = tert-$C_4H_9$ | 50 |

[a] After correction on E1 component; *cf* Table IV.

buffered by 0·15M triethylamine). The two products (*A* and *B*) were isolated by preparative vapour-phase chromatography and identified by NMR and mass-spectra as 2,3-dimethylnon--1-ene and 2,3-dimethylnon-2-ene, respectively (carbonium ion rearragement). An additional product (*C*) was found also in the corresponding reaction of the tosylate *II*; R = iso-$C_3H_7$. By analogy with the results reported by Saunders[21] for the reaction of 2-methylpentyl tosylate, the product *C* was assigned configuration of 2-methylnon-2-ene.

Evidently, therefore, competition between E1 and E2 processes occurs in the two reactions. Mechanistic dissection into the E1 and E2 components was performed using the procedure described by Colter and McKelvey[22]. The results are summarized in Table IV.

In the reaction of all tosylates *I* and the unbranched tosylates *II*, the proportion of rearranged products was negligibly small. Comparison of the reaction rates[23] measured in 0·45M potassium tert-butoxide and in 0·15M triethylamine in tert-butanol shows that the contribution of E1 component to the former process cannot be greater than 5%, except for the above two tosylates *II* (R = tert-$C_4H_9$ and iso-$C_3H_7$).

General absence of rearranged products in the reaction of tosylates *I* and *II* with potassium tert-butoxide in dimethylformamide is taken as a satisfactory evidence that the overall reaction represents a clean E2 process.

TABLE IV

E2 and E1 Components in the Reaction of Tosylates *II* with 0·45M Potassium Tert-Butoxide in Tert-Butanol

| Tosylate | Component | Overall %[a] | Isomer-olefin distribution |
|---|---|---|---|
| *II*; R = tert-$C_4H_9$ | E2 | 16 | *trans-IV* (64·5%), *cis-IV* (35·5%) |
| | E1 | 84 | *trans-IV* (53·5%), *cis-IV* (0·5%), *A* (40%), *B* (6%) |
| *II*; R = iso-$C_3H_7$ | E2 | 70 | *trans-IV* (14·5%), *cis-IV* (13·5%), *V* (72%) |
| | E1 | 30 | *trans-IV* (16%), *cis-IV* (2·0%), *V* (64%), *C* (18%) |

[a] % E2 + % E1 = 100.

## Anti-*Elimination Induced by Dissociated Alkoxide Base*

The olefin-isomer distribution in the reaction of tosylates *I* and *II* with potassium tert-butoxide in dimethylformamide is summarized in Tables V and VI, respectively. A pronounced dependence of percentage of the individual isomers on the substituent R is immediately apparent from the data. For some of the isomers (*cis-III* and *cis-IV* from *I*), the changes induced by a gradual increasing the structural complexity of R are continuous. For the other isomers, however, the changes are not continuous, which suggest that several factors operating in opposite directions participate in their formation.

Different steric as well as polar effects can be involved in the observed trends. In order to disentangle the former (steric) effects from the latter (polar) ones, we focus our main attention on the *trans*/*cis* ratios in the two tosylate series. Because the operation of polar effects in the formation of corresponding *trans*- and *cis*-alkenes has to be very similar, the polar contribution in the individual *trans*/*cis* ratios is assumed to be practically cancelled. Steric effects can be therefore separately analyzed on these grounds.

*Alkyl–alkyl interactions*: A qualitatively similar dependence of the values of *trans-IV*/*cis-IV* on R is found in both the positionally isomeric series *I* and *II* (Table V and VI, respectively). The values which, notably, are always greater than

TABLE V

Olefin-Isomer Distribution in the Reaction of Tosylates *I*, $RCH_2CHOTsC_5H_{11}$, with Potassium Tert-Butoxide in Dimethylformamide

| R | $RCH_2CH{=}CHC_4H_9$ (*III*) | | | $RCH{=}CHC_5H_{11}$ (*IV*) | | |
|---|---|---|---|---|---|---|
| | % *trans* | % *cis* | *trans*/*cis* | % *trans* | % *cis* | *trans*/*cis* |
| H | 20·4 | 7·0 | 2·9 | 72·6 | | — |
| $CH_3$ | 24·2 | 6·2 | 3·9 | 53·3 | 16·3 | 3·3 |
| $C_2H_5$ | 34·6 | 10·1 | 3·4 | 45·2 | 10·1 | 4·5 |
| n-$C_3H_7$ | 38·6 | 10·4 | 3·7 | 38·6 | 10·4 | 3·7 |
| iso-$C_3H_7$ | 40·3 | 19·8 | 2·0 | 34·8 | 5·1 | 6·8 |
| tert-$C_4H_9$ | 13·7 | 24·0 | 0·57 | 60·9 | 1·4 | 43·5 |

TABLE VI

Olefin-Isomer Distribution in the Reaction of Tosylates *II*, $RCHOTsCH_2C_5H_{11}$, with Potassium Tert-Butoxide in Dimethylformamide

| R | $RCH{=}CHC_5H_{11}$ (*IV*) | | | $R^1R^2C{=}CHC_6H_{13}$ (*V*) | | |
|---|---|---|---|---|---|---|
| | % *trans* | % *cis* | *trans*/*cis* | % *trans* | % *cis* | *trans*/*cis* |
| $CH_3$ | 20·7 | 7·7 | 2·7 | 71·6 | | — |
| $C_2H_5$ | 24·8 | 5·3 | 4·7 | 53·2 | 16·7 | 3·2 |
| n-$C_3H_7$ | 33·8 | 11·8 | 2·9 | 32·3 | 12·1 | 2·7 |
| iso-$C_3H_7$ | 28·9 | 1·2 | 24·0 | 69·9 | | — |
| tert-$C_4H_9$ | 98·2 | 1·8 | 54·5 | — | — | — |

unity, do not change significantly on lengthening the alkyl chain in R (R = $CH_3$, $C_2H_5$, n-$C_3H_7$). However, a gradual and pronounced increase of the values results from branching the substituent R (R = iso-$C_3H_7$ and tert-$C_4H_9$). In accord with a general consent in interpreting analogous results in other elimination series[1,14], we can assume that interactions between the adjacent alkyls on $C_\alpha$ and $C_\beta$ (eclipsing effects) are the main factor which accounts for the observed trend.

*'Neohexyl anomaly'*: A strikingly different trend is found for the values of *trans-III*/*cis-III* ratios from the tosylates *I*. As Table V shows, the values from the unbranched tosylates (R = H, $CH_3$, $C_2H_5$, n-$C_3H_7$) are again practically independent on R and comparable with those obtained for the corresponding positional isomers (*trans-IV*/*cis-IV*; Table V). Surprisingly, however, introduction of branching (R = iso-$C_3H_7$, tert-$C_4H_9$) does not lead to an increase but to a pronounced decrease of the value of *trans-III*/*cis-III* ratio; for *I*; R = tert-$C_4H_9$, the value is already significantly lower than unity. This, evidently, constitutes an anomaly from the standpoint of eclipsing effects, for, as a simple consideration and a direct experimental evidence[14] show, the interactions between alkyls in the formation of the branched *cis*-alkenes *III* should be greater than those found for the unbranched analogues.

To our knowledge, no precendent for such an anomaly exists in elimination of aliphatic tosylates under conditions where dissociated* alkoxide base is expected to prevail. On the other hand, *trans*/*cis* ratios lower than unity are very frequent[8,11,12] in the reaction induced by the associated tert-butoxide base: as we shall see in the following section, preferential *cis*-olefin formation represents for the tosylates *I* and *II* a usual rather than exceptional outcome of the reaction.

Accordingly, a question may be raised, whether the associated base is not also involved in the reaction of the "neohexyl" tosylate (*I*; tert-$C_4H_9$) with potassium tert-butoxide in dimethylformamide. *A priori*, such a possibility cannot be excluded: whereas a prevalence of the dissociated base was repeatedly established in the reaction of unbranched tosylates (*vide supra*), a very pronounced operation of the associated form was demonstrated, in dimethylformamide, in the reaction of a sterically encumbered cyclodecyl tosylate[10,17]. Accordingly, to resolve this question, we have now examined the effect of the potassium-ion separating agent, dicyclohexyl-18-crown-6-ether (*VI*), in the reaction of the "neohexyl" tosylate. The finding that the olefin-isomer distribution is practically the same in the absence as well as in the presence of the crown ether *VI* (Table VII; entry *1* and *2*, respectively) provides, on basis of our previous arguments[9], a satisfactory evidence that the associated base is not substantially involved in the reaction. Admittedly, it might be argued

* Similar situation holds also for other derivatives which possess a neutral leaving group. The exceptions reported by Bartsch and Bunnett[24] presumably resulted from a subsequent isomerization[25]. In contrast, preferential *cis*-alkene formation is quite common in the reaction of quaternary ammonium salts[1,5–7]; several explanations[5,7,9] were proposed for it.

that neither the dissociated base is involved in the reaction; however, the finding that olefin-isomer distribution from solvolysis of the tosylate in dimethylformamide is entirely different (Table VII; entry *3*), excludes also the latter possibility. Therefore, the dissociated tert-butoxide base actually operates in the anomalous reaction.

In consideration of the anomaly, we may now progress to the role of leaving group. The olefin-isomer composition data obtained from the corresponding reaction of the chloro analogue of the tosylate *I*; R = tert-$C_4H_9$ are presented in Table VII (entry *4*). The complete suppression of the anomaly resulting from substitution the tosyloxy residue which is bulky and unsymmetrical by the chloro group which is small and symmetrical clearly show that steric requirements of leaving group deserve a particular attention.

*Extension of the anomaly*: If steric requirements of tosyloxy-group are responsible for the unexpectedly low *trans-III*/*cis-III* ratios from the branched tosylates *I*, an extension of the anomaly should result from increasing the effective size of the tosyloxy group. It is known that solvation may change the size of leaving groups. In aprotic solvents, the solvation of neutral leaving groups is not large. In protic solvents, on the other hand, a marked increase in effective size of leaving group can be attained by hydrogen bonding[26]. For tosyloxy group which bears three oxygen atoms the effects of hydrogen bonding may be particularly strong.

Ethanol is a very convenient protic solvent. Accordingly, we used the reaction of tosylates *I* with potassium ethoxide in ethanol as a probe for examination of the effect of leaving group solvation. The mechanistic evidence which is available for E2 reactions in this base–solvent system is much less complete[11,12] than that we presented for potassium tert-butoxide-dimethylformamide combination. Nonetheless, it allows us to expect that the main mechanistic feature of the reaction in the two base–solvent systems (*anti*-stereochemistry, dissociated form of base, absence

TABLE VII

The Effect of Base, Crown-Ether *VI* and Leaving Group on Olefin-Isomer Distribution in Elimination of the Derivatives Tert-$C_4H_9CH_2CHXC_5H_{11}$ Performed in Dimethylformamide

| X | Base | tert-$C_4H_9CH_2CH{=}CHC_4H_9$ | | tert-$C_4H_9CH{=}CHC_5H_{11}$ | |
|---|---|---|---|---|---|
| | | % *trans* | % *cis* | % *trans* | % *cis* |
| OTs | tert-$C_4H_9OK$ | 13·7 | 24·0 | 60·9 | 1·4 |
| OTs | tert-$C_4H_9OK$ — *VI*[a] | 11·6 | 23·5 | 63·5 | 1·4 |
| OTs | solvolysis[b] | 21·5 | 13·0 | 64·6 | 1·2 |
| Cl | tert-$C_4H_9OK$[c] | 30·9 | 9·6 | 59·0 | 0·5 |

[a] In molar ratio 1 : 1, [b] at 100°C; [c] at 50°C.

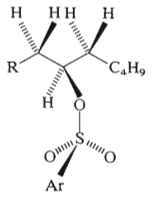
of solvolysis), at least for the tosylates *I*, are very similar. Evidently, the basicity in the two systems is different. However, a satisfactory evidence was presented[27] that difference in basicity does not influence significantly magnitude of *trans/cis* ratios. Accordingly, the values of the ratios *trans-III/cis-III* and *trans-IV/cis-IV* obtained for the tosylates *I* in the two base–solvent combinations are compared in Table VIII.

With a single exception (*III*, R = tert-$C_4H_9$), the values of *trans-III/cis-III* as well as *trans-IV/cis-IV* are always substantially lower (approximately by a factor of 2) in the protic ethanol than in the aprotic dimethylformamide. In actual fact, the values which are now found in ethanol are invariantly lower than it would correspond to the lowest theoretical[28] estimate for the alkyl–alkyl interactions in the optimal (synclinal) arrangement. Therefore, an extension of the "neohexyl" anomaly by solvation of the leaving group is indeed attained.

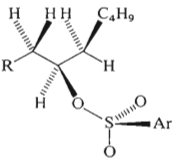
*Interactions between tosyloxy group and adjacent alkyls*: It was already suggested by Saunders[21] that interactions between tosyloxy group and adjacent alkyls may influence values of *trans/cis* ratios. A simple conformational model was proposed in which the interactions disfavour the formation of *trans*-isomers (Scheme 2). Our experimental evidence concerning the solvent effect (Table VIII) lends a full support to this conformational prediction.


SCHEME 2

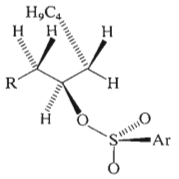
A further elaboration of the Saunders' model may provide a very plausible explanation why the *trans-III/cis-III* ratios in the reaction of the branched tosylates *I* are particularly low (neohexyl anomaly). The expected conformational situation is visualized in Scheme 3. When substituent R is an unbranched group, the transoid conformation A represents presumably the most favourable arrangement for *trans-III* as well as *trans-IV* formation from the tosylates *I*. A successive branching of R leads to a gradual increase of steric compression in *A*, which cannot be alleviated much by a simple torsion of the arylsulphonyl group around the $C_\alpha$—O bond. However, when the compression is strong enough, it may be relieved markedly by a simultaneous torsion of the adjacent n-pentyl group (conformations *B* and *C*, respectively).



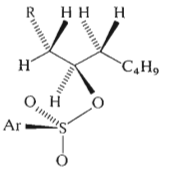

*A*




*B*




*C*




*D*

SCHEME 3

TABLE VIII

*trans/cis* Ratios in the Reaction of Tosylates *I*, $RCH_2CHOTsC_5H_{11}$, with Potassium Tert-Butoxide in Dimethylformamide (*A*) and with Potassium Ethoxide in Ethanol (*B*), Respectively

| R | $RCH_2CH{=}CHC_4H_9$ (*III*) | | $RCH{=}CHC_5H_{11}$ (*IV*) | |
|---|---|---|---|---|
| | *A* | *B* | *A* | *B* |
| H | 2·9 | 1·5 | — | — |
| $CH_3$ | 3·9 | 2·0 | 3·3 | 2·0 |
| $C_2H_5$ | 3·4 | 1·6 | 4·5 | 2·0 |
| *n*-$C_3H_7$ | 3·7 | 1·7 | 3·7 | 1·7 |
| iso-$C_3H_7$ | 2·0 | 1·1 | 6·8 | 3·3 |
| tert-$C_4H_9$ | 0·6 | 0·6 | 43·0 | 20·0 |

A much smaller, if any, relief of the strain would result from the torsion of the branched R group owing to a more severe synclinal interactions (*D*). In this way, the formation of *cis-III* (in *B*) as well as *trans-IV* (in *B* or *C*) alkenes becomes energetically more advantageous than the formation of *trans-III* alkene, because the latter (in *A* or *D*) cannot evade the steric compression.

### Anti-*Elimination Induced by Associated Alkoxide Base*

The approximate olefin–isomer composition corresponding to the *anti*-pathway in the reaction of tosylates *I* and *II* with potassium tert-butoxide in tert-butanol is summarized in Tables IX and X, respectively. Striking difference between these data and those which we analyzed in the preceding section is immediately apparent. Specifically, it holds for the distribution of the geometrical isomers. The values of *trans*/*cis* ratios which are now found for the associated tert-butoxide base are always (with a single exception of *IV*, R = tert-$C_4H_9$, from *I*; R = tert-$C_4H_9$) lower than unity, in an almost exact opposite to the situation found above for the reaction with the dissociated base.

This difference, however remarkable, does not come as a complete surprise. Analogous situation was already demonstrated[9,11,12] for a number of other open-chain reactants (tosylates and halides). A very general consent was already reached[9,11–12] that interactions between participating base and reactant, which are presumably only minor for the dissociated base form but very strong for the associated one, are the responsible factor which accounts for the difference between the two alternative reactions.

TABLE IX

Olefin-Isomer Distribution in the *anti*-Elimination of Tosylates *I*, $RCH_2CHOTsC_5H_{11}$, with Potassium Tert-Butoxide in Tert-Butanol

| R | $RCH_2CH{=}CHC_4H_9$ (*III*) | | | $RCH{=}CHC_5H_{11}$ (*IV*) | | |
|---|---|---|---|---|---|---|
| | % *trans* | % *cis* | *trans*/*cis* | % *trans* | % *cis* | *trans*/*cis* |
| H[a] | 4·9 | 14·5 | 0·34 | 80·6 | | — |
| $CH_3$[a] | 8·0 | 18·1 | 0·44 | 23·0 | 50·9 | 0·45 |
| $C_2H_5$[a] | 12·0 | 33·6 | 0·36 | 16·1 | 38·3 | 0·42 |
| n-$C_3H_7$[a] | 13·6 | 36·4 | 0·37 | 13·6 | 36·4 | 0·37 |
| iso-$C_3H_7$[b] | 11·9 | 57·4 | 0·21 | 12·0 | 18·7 | 0·64 |
| tert-$C_4H_9$[b] | 11·7 | 53·7 | 0·22 | 31·3 | 3·3 | 9·50 |

[a] The contribution of *syn*-pathway was presumably only minor (*vide supra*) and it was neglected; [b] corrected on contribution of *syn*-pathway in the formation of the *trans-III* isomer (*cf.* Table III).

However, the nature and operational mode of the interactions induced by the associated base have not been, as yet, satisfactorily explained[25]. For elucidation of this intriguing point, it is necessary to know how the interactions depend on the alkyl structure of reactants. In this respect, a detailed examination of the present results can be very useful.

*Interactions between associated base and alkyls*: Recently, Bartsch[12] proposed a simple model for repulsive interactions between base and alkyls in reactant (Scheme 4). In this model, it is assumed that the repulsion is always much greater in the transition state leading to the *trans*- (*A*) than to the *cis*-alkene (*B*), because in the latter the base can be tilted to that side of reactant where only hydrogens are placed. In this way, the selective hindrance to approach of the sterically "outsized" associated base can be viewed to be responsible for the extremely low values of *trans*/*cis* ratios observed in the reaction.

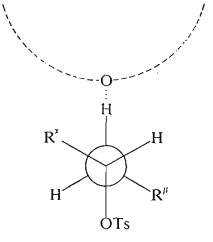
On basis of this model, we now attempt to analyse, in the tosylate series *I* and *II*, whether and in which way the selective hindrance depends on steric bulk of the adjacent alkyls. Obviously, such an analysis cannot be based on a simple comparison of the individual *trans*/*cis* ratios in the reaction with the associated base, the values being controlled not only by the interactions between base and alkyls but also by the interactions in the reactant alone (alkyl–alkyl and alkyl–tosyloxy interactions). On the other hand, the ratios of the corresponding *trans*/*cis* ratios obtained respectively in the reaction with the dissociated (in dimethylformamide) and with the associated (in tert-butanol) tert-butoxide base may give us a good measure of the hindrance to the latter (associated) base approach: because the interactions which

TABLE X

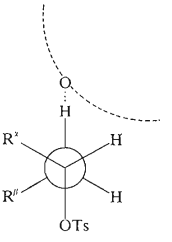
Olefin-Isomer Distribution in the *anti*-Elimination of Tosylates *II*, $RCHOTsCH_2C_5H_{11}$, with Potassium Tert-Butoxide in Tert-Butanol

| R | $RCH{=}CHC_5H_{11}$ (*IV*) | | | $R^1R^2C{=}CC_6H_{13}$ (*V*) | | |
|---|---|---|---|---|---|---|
| | % *trans* | % *cis* | *trans*/*cis* | % *trans* | % *cis* | *trans*/*cis* |
| $CH_3$ [a] | 5·5 | 14·5 | 0·38 | 80 | | — |
| $C_2H_5$ [a] | 7·6 | 18·1 | 0·42 | 23·3 | 51·0 | 0·46 |
| n-$C_3H_7$ [a] | 12·1 | 34·1 | 0·36 | 16·3 | 37·5 | 0·43 |
| iso-$C_3H_7$ [b] | 10·6 | 14·1 | 0·75 | 75·3 | | — |
| tert-$C_4H_9$ [b] | 47·5 | 52·5 | 0·90 | — | — | — |

[a] The contribution of *syn*-pathway was presumably only minor (*vide supra*) and it was neglected; [b] corrected on contribution of *syn*-pathway in the formation of the *trans-IV* isomer (*cf.* Table III) and also on incursion of solvolysis (*cf.* Table IV).




*A*




*B*

SCHEME 4

*I* → *III*: $R^{\alpha} = RCH_2$, $R^{\beta} = n\text{-}C_4H_9$
*I* → *IV*: $R^{\alpha} = n\text{-}C_5H_{11}$, $R^{\beta} = R$
*II* → *IV*: $R^{\alpha} = R$, $R^{\beta} = n\text{-}C_5H_{11}$

concern the reactant alone are probably very similar in both the reactions with the alternative base forms, their contribution in the complex ratios has to be nearly cancelled. The complex ratios calculated for the three main elimination processes *I* → *III*, *I* → *IV* and *II* → *IV* are summarized in Table XI.

As the data of Table XI show, a mere lengthening of alkyl chain does not affect significantly the complex ratio, the values being, for unbranched R group, practically constant (~10) in all the three different processes. The branching of alkyl chain, however, does affect the values of the ratio. In the process *II* → *IV*, a pronounced increase of the value results from the successive branching of the substituent R

TABLE XI

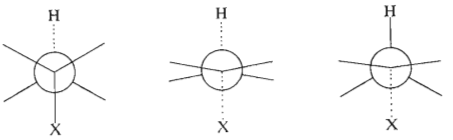
Ratios of *trans*/*cis* Ratios Obtained in *anti*-Elimination of Tosylates *I* and *II* with the Dissociated (in dimethylformamide) and with the Associated (in tert-butanol) Tert-Butoxide Base

| R | (*trans*/*cis*) $HCON(CH_3)_2$/(*trans*/*cis*) tert-$C_4H_9OH$ | | |
|---|---|---|---|
| | *I* → *III* | *I* → *IV* | *II* → *IV* |
| $CH_3$ | 8·5 | 7·4 | 7·1 |
| $C_2H_5$ | 8·9 | 10·7 | 11·2 |
| n-$C_3H_7$ | 9·5 | 10·0 | 8·1 |
| iso-$C_3H_7$ | 10·0 | 10·6 | 32·0 |
| tert-$C_4H_9$ | 2·6 | 4·6 | 60·5 |

indicating a gradual increase in the base approach hindrance, in agreement with the Scheme 4. In the processes $I \rightarrow III$ and $I \rightarrow IV$, in contrast, a significant decrease of the value is induced by an analogous structural change (R = tert-$C_4H_9$).

Accordingly, we see that increase in steric bulk of R leads in the latter two processes to a decrease in base-approach hindrance, in an apparent discord with the Scheme 4.

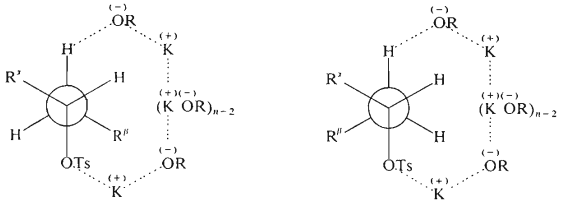
*Steric compression and spectrum of transition states*: For understanding of this peculiar situation it is essential to note that both the cases, where the base-approach hindrance is anomalously low, relate to the tosylate *I*; R = tert-$C_4H_9$, which was anomalous already in the reaction with the dissociated base form (neohexyl anomaly). As we proposed in the preceding section, steric compression of tosyloxy group is responsible for the latter anomaly; a partial decompression is attained by conformational changes which favour the *cis-III* isomer formation (Scheme 3).




Elcb-like E2-central El-like

SCHEME 5

However, there exists a complementary, and a more general, mode of steric decompression, by a shift in the Elcb-like – El-like spectrum of transition states. Namely, it is known for E2 reactions of quaternary ammonium salts[29–31] that steric compression introduced by branching in the reactants tends to lengthen $C_\alpha$—X bond and provides thus a driving force for shifting the transition state from the usual Elcb-like – E2-central region to the El-like side of the spectrum, where the strain is more effectively reduced (Scheme 5). An analogous shift occurs presumably also within the elimination series *I* and *II*, as evidenced by apparent changes in positional orientation. A clear-cut Hofmann orientation (preferential formation of the least substituted isomer) is obtained in the reaction of all the unbranched tosylates *I* and *II* (Tables IX and X and also V and VI), which is generally regarded to be indicative for the Elcb-region. In contrast, however, Saytzeff orientation (preferential information of the most substituted isomer) is found for the most branched tosylates (*I*; R = tert-$C_4H_9$; *II*, R = iso-$C_3H_7$), which suggests that the reaction already takes place in the E2-central – El-like region.




SCHEME 6

$I \rightarrow III$: $R^{\alpha} = CH_2R$, $R^{\beta} = n\text{-}C_4H_9$.
$II \rightarrow IV$: $R^{\alpha} = R$, $R^{\beta} = n\text{-}C_5H_{11}$

We propose that the shift is responsible also for the anomalies in the base-approach hindrance (Table XI). A flattening of transition state on $C_\alpha$ which is expected in the E2-central – E1-like region (Scheme 6) will increase the $R_\alpha$...base clearance, reducing thus effectively the base-approach hindrance in the reaction of the branched tosylates. The circumstance that a decrease of the hindrance with alkyl branching is observed in the processes $I \rightarrow III$ and $I \rightarrow IV$ but not in $II \rightarrow IV$ is in a reasonable accord with this suggestion. In the latter process, the increment in the alkyl–base interactions which is induced by branching of R is presumably so large that it cannot be compensated in full by flattening the transition state.

*Interactions between associated base and leaving group*: The above analysis showed that the observed pattern of base-approach hindrance for the tosylates *I* and *II* is in a reasonable agreement with the Bartsch' conformational model, when accompanying changes in transition-state geometry are taken into account. Despite it, serious objections may still be raised against the Bartsch' model. Namely, we already objected[9] that the model fails to explain why sterically outsized dissociated alkoxides never produce low *trans*/*cis* ratios as it is common for the associated base. A recent, and very relevant evidence shows[32], in actual fact, that a gradual increasing of steric bulk of dissociated base does not lead to a decrease but rather to an increase of the value of these ratios.

As an explanation, Schlosser[33,34] together with us proposed that attractive interactions (coordination) between counterion of the associated base and leaving group with unshared electron pairs control geometry of transition state and by enforcing its pseudo-cyclic arrangement give rise to a selective base-approach hindrance in *trans*- but not in *cis*-alkene formation. The situation is visualized for the elimination processes $I \rightarrow III$ and $II \rightarrow IV$ in the Scheme 6, in a correspondence with the original Schlosser's proposal[33].

In our opinion, the present results do not agree persuasively with the pseudocyclic model. As a simple consideration of the model suggests, the base-approach hindrance in the processes $I \rightarrow$ *trans-III* and $II \rightarrow$ *trans-IV* should be more or less independent on the branching of substituent R, in discord with the data of Table XI.

However, it would be unwise to dismiss this concept in whole on such grounds. It is quite possible that steric interactions between the base and alkyls are prohibitively large in the pseudocyclic arrangement for *trans*-alkene formation. Accordingly, we propose to consider the attractive interactions within the framework of the Bartsch's model. Evidently, the presumed tilting of associated base gets its counterion to a closer proximity of leaving group in the arrangement *B* than in *A* (Scheme 4) and the attraction involved provides additional support for the *cis*-alkene formation.

*Base approach hindrance and positional orientation*: On comparison with the impressive effect which exerts base association on distribution of geometrical isomers (*vide supra*), the corresponding effect on positional orientation is indeed very small (Table XII). As we already pointed out in a previous paper[25], lowering of base strength by ion-association may induce changes in positional orientation in opposite direction than those which would arise from shielding the associated base approach in the transition state. Accordingly, a counterbalance of the two factors may be expected. Nonetheless, it may be noted for the most branched tosylate *I*, R = tert-$C_4H_9$, that the proportion of the "more shielded" positional isomer (*trans-IV*; R = tert-$C_4H_9$) is significantly greater in dimethylformamide than in tert-butanol. This, obviously, agrees well with preponderance of the selective base-approach hindrance in the latter reaction.

TABLE XII

Comparison of *trans-IV*/*trans-III* and *cis-IV*/*cis-III* Ratios from *anti*-Elimination of Tosylates *I*, $RCH_2CHOTsC_5H_{11}$, with the Dissociated (in dimethylformamide) and with the Associated (in tert-butanol) Tert-Butoxide Base

| R | *trans-IV*/*trans-III* | | *cis-IV*/*cis-III* | |
|---|---|---|---|---|
| | $HCON(CH_3)_2$ | tert-$C_4H_9OH$ | $HCON(CH_3)_2$ | tert-$C_4H_9OH$ |
| $CH_3$ | 2·2 | 2·9 | 2·6 | 2·8 |
| $C_2H_5$ | 1·3 | 1·3 | 1·0 | 1·1 |
| n-$C_3H_7$ | 1·0 | 1·0 | 1·0 | 1·0 |
| iso-$C_3H_7$ | 0·86 | 1·0 | 0·26 | 0·32 |
| tert-$C_4H_9$ | 4·4 | 2·7 | 0·06 | 0·06 |

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Translated by the author (J. Z.).