Rearrangements of Pinane Derivatives. Part III.[1] Solvolysis of the 2-Pinanyl *p*-Nitrobenzoates

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Methanolysis of the 2-pinanyl *p*-nitrobenzoates in the presence of base gives a mixture of products including both *cis*- and *trans*-methyl 2-pinanyl ethers from both esters. In contrast, other substitution products show a rigid retention of stereochemistry. It is suggested that each ester forms a delocalised ion, and that these ions can subsequently be interconverted. The results contrast with data reported from the study of the nopinol system, but both sets of results have been shown to be consistent with a mechanism of interconversion of ions in which two possible reaction paths exist, the direction of reaction being controlled by the substituent on C-2. Elimination products fit this general pattern except for a very high yield of α-pinene from the *cis*-ester, which may arise from elimination within an intimate ion pair, rather than from the 'free' ion. The *trans*-ester, in contrast, gives an intimate ion pair which undergoes collapse rather than elimination.

THE 2-pinanols, originally known as methyl nopinol [2] and pinene hydrate [3] have been relatively little used in mechanistic studies, probably on account of their ready decomposition by acids. Burrows and Eastman [4] showed that the rearrangements accompanying esterification with acetic anhydride were stereospecific, methyl nopinol giving bornyl acetate and pinene hydrate giving α-fenchyl acetate, though both also gave α-terpinyl acetate. This experiment also confirmed the stereochemistry of the alcohols; further proof has recently been obtained by Erman,[5] who showed that the ⁻OH and *gem*-dimethyl bridge of methyl nopinol must be *cis* to each other.

Reactions of the *p*-nitrobenzoates of the 2-pinanols were originally studied by Abraham,[6] who found that the *cis*-ester rearranged to give bornyl *p*-nitrobenzoate and the *trans*-ester the corresponding α-fenchyl ester. He also studied elimination reactions of the esters, obtaining mixtures of olefins which differed quantitatively between the two substrates. Both rearranged esters were considered to be formed by internal return from an ion pair, the formation of pure *endo*-isomers in each case being consistent with the well-known formation of the *endo*-bornyl chloride from pinene hydrochloride.

The ready formation of ion pairs during solvolysis of pinyl esters was also observed by Winstein,[7] studying the nopinols, which differ from the pinanols in the absence of the C-2-methyl group. The bromobenzenesulphonate of β-nopinol was found to yield, on solvolysis, only 32% of solvolysis products, together with 43% of apobornyl bromobenzenesulphonate, and 25% of a mixture of the bromobenzenesulphonates of the isomeric *exo*-alcohols, apisoborneol, *exo*-camphenilol and β-fenchoisocamphorol. The formation of *exo*-esters contrasts with the results reported above. Products arising from separation, rather than collapse of the ion pair showed a similar reaction pattern, consisting of the acetates of the four alcohols listed above, together with the acetate of norterpineol. There was no obvious explanation as to why a methyl substituent should produce such a drastic change in a reaction path.[8]

Winstein's work was further confirmed by Kirmse [9] who showed that apoisoborneol is a major product of the solvolysis of *cis*-2-nopinyl *p*-nitrobenzoate in aqueous

[1] Part II, Claudia M. Williams and D. Whittaker, *J. Chem. Soc.* (*B*), 1971, 673.
[2] O. Wallach, *Annalen*, 1907, **356**, 227.
[3] A. Lipp, *Chem. Ber.*, 1923, **56**, 2098.
[4] W. D. Burrows and R. H. Eastman, *J. Amer. Chem. Soc.*, 1959, **81**, 245.
[5] T. W. Gibson and W. F. Erman, *Tetrahedron Letters*, 1967, 905.
[6] N. A. Abraham and M. Vilkas, *Bull. Soc. chim. France*, 1960, 1450; N. A. Abraham, *Ann. Chim.* (*France*), 1960, 961.
[7] E. C. Friedrich and S. Winstein, *J. Amer. Chem. Soc.*, 1964, **86**, 2721.
[8] D. V. Banthorpe and D. Whittaker, *Quart. Rev.*, 1966, **20**, 373.
[9] W. Kirmse and R. Siegfried, *J. Amer. Chem. Soc.*, 1968, **90** 6564.

acetone. Kirmse also showed that formation of *exo*-products was unlikely to result from control of the reaction by a counterion by studying the photolysis of 2-nopinyl *p*-toluenesulphonyl hydrazone. This reaction is believed to proceed *via* the diazo-compound, giving an intermediate in a reaction in which nitrogen is the leaving group, and thus unlikely to influence the products. The main product was apoisoborneol, which is consistent with reaction stereochemistry being controlled by the intermediate not its environment.

EXPERIMENTAL

The *p*-nitrobenzoate esters of the *cis*- and *trans*-2-pinanols were prepared by the methods of Abraham,[6] and had similar physical properties, α-fenchene was prepared by the method of Hückel,[10,11] and terpinolene was a gift from Mr. E. J. Vize of Bush Boake Allen, Ltd., Widnes.

The methyl ethers of borneol, α-fenchol, α-terpineol, and the pinanols were prepared by reaction of the potassium compound of the alcohol with methyl iodide. The *p*-nitrobenzoates of borneol and fenchol were prepared by reaction between the alcohol and the acid chloride in pyridine. Methanol was purified by the method of Vogel.[12]

Kinetics.—Kinetic studies were carried out by conventional methods, reaction samples being removed at intervals and poured into water to stop the reaction. The base remaining was titrated with dilute hydrochloric acid, using Bromothymol Blue as indicator. Infinity values were obtained by sealing samples in Pyrex tubes, and heating them for 72 hr. at 85°, to ensure complete reaction of bornyl and α-fenchyl esters.

Product Studies.—Product studies were carried out under the same conditions as kinetic experiments, except that reactions were in sealed ampoules. Bornyl and α-fenchyl *p*-nitrobenzoates were decomposed by lithium aluminium hydride reduction before analysis. Analyses were carried out by g.l.c. on a Perkin-Elmer F.11 chromatograph using a 150 ft. capillary column coated with di-isodecyl phthalate. Identities of peaks were confirmed by i.r. spectroscopy on samples obtained by preparative scale g.l.c. on a Wilkins Aerograph A700 with an 18 ft. × ⅜ in. copper column packed with 12% Carbowax 20M. on 60—80 mesh Celite. Quantitative data were obtained by the method of peak height × retention time summation. Correction factors to give results as moles% were obtained by using samples of known amounts of each product with known amounts of β-pinene. Results were reproducible to 1%, and are reported to this accuracy; all amounts below this figure are reported as 1%.

RESULTS AND DISCUSSION

A study of the kinetics of solvolysis of the *cis*- and *trans*-2-pinanyl *p*-nitrobenzoates in methanol containing 0·033M-sodium methoxide showed that the former gave good first-order kinetics over the first 80% reaction, and the latter over only the first 40%, due to concurrent bimolecular solvolysis and internal return from an ion pair to a more stable ester. Within these ranges, the rate constants for solvolysis at 40·0° in methanol containing 0·033M sodium methoxide were for *cis*-2-pinanyl p-nitrobenzoate, $k_1 = 2{\cdot}5 \times 10^{-4}$ sec.$^{-1}$ and for *trans*-2-pinanyl *p*-nitrobenzoate, $k_1 = 4{\cdot}2 \times 10^{-6}$ sec.$^{-1}$.

Product studies (see later) suggest that the rate for the *cis*-ester is probably correct within the broad limits imposed by ignoring internal return from an intimate ion pair to the substrate. However, the *trans*-ester undergoes simultaneously a reaction, presumably bimolecular, to give *trans*-2-pinanol, and forms α-fenchyl *p*-nitrobenzoate, presumably by internal return from an ion pair. These reactions, which affect the kinetics in the later stage of reaction, must also modify the rates measured in the early stages of reaction, and must be added to the limits of error imposed by neglecting internal return of an intimate ion pair to substrate in the *trans*-ester case. Despite this, the rates are in good relative agreement with those observed earlier[6] for the hydrolysis of these esters in aqueous 90% acetone at 49·6°, whence, for the *cis*-ester, $k_1 = 2{\cdot}8 \times 10^{-4}$ sec.$^{-1}$ and for the *trans*-ester, $k_1 = 8{\cdot}4 \times 10^{-6}$ sec.$^{-1}$.

Although the tendency of these systems to undergo internal return from ion pairs makes detailed interpretation of titrimetric rate differences meaningless, our data, compared with published data for the hydrolysis of 2-methyl *endo*-norborn-2-yl *p*-nitrobenzoate[13] suggests that our *cis*-ester reacts more rapidly than an unaccelerated ester in similar conditions by a factor of *ca.* 10^6, comparing well with the rate increase of 10^5 which Winstein found for β-nopinyl esters over apobornyl esters. We suggest that the acceleration of solvolysis of our ester results from the same cause, that is, by participation of the σ electrons of the C(1)–C(7) bond to give the ion (I), which is a methyl substituted version of (V). The slightly lower value for the acceleration of the *trans*-ester probably results from formation of the ion (II), corresponding to (VI), receiving less assistance from σ-bond participation due to the absence of the *gem*-dimethyl group from the appropriate bridge. This effect is enough to offset the increase in ground-state energy of this ester caused by interaction between the *gem*-dimethyl bridge and the *p*-nitrobenzoate group.

The products of alkaline methanolysis of the *cis*- and *trans*-2-pinanyl *p*-nitrobenzoates have been determined, and are reported in the Table.

Both esters undergo both unimolecular and bimolecular reactions. The bimolecular reaction, which yields unrearranged alcohol from each ester, is clearly base catalysed, and presumably proceeds by a $B_{Ac}2$ mechanism. The yields of alcohols derived by this reaction, as a % of the total ester, are given in columns 1 and 2 of the table.

The remainder of the reaction of each ester is by fission of the alkyl–oxygen bond. The presence of borneol and α-fenchol among the reaction products indicates that the first stage of the reaction is probably the formation of an intimate ion pair, which can undergo internal return either to regenerate starting material or to generate the rearranged ester, the *cis*-ester yielding

[10] W. Hückel and H.-J. Kern, *Annalen*, 1965, **687**, 40.
[11] E. Pulkkinen, *Ann. Acad. Sci. Fennicae*, Ser. A.II, No. **74**.
[12] A. I. Vogel, 'A Text-Book of Practical Organic Chemistry,' Longmans, London, 1951, 2nd edn., p. 168.
[13] S. Ikegami, D. L. V. Jagt, and H. C. Brown, *J. Amer. Chem. Soc.*, 1968, **90**, 7124.

bornyl *p*-nitrobenzoate and the *trans*-ester yielding α-fenchyl *p*-nitrobenzoate. The esters thus formed then solvolyse by a $B_{Ac}2$ mechanism to give borneol and fenchol, the yields of which are reported, as a % of the total unimolecular reaction, in columns 3 and 4 of the table.

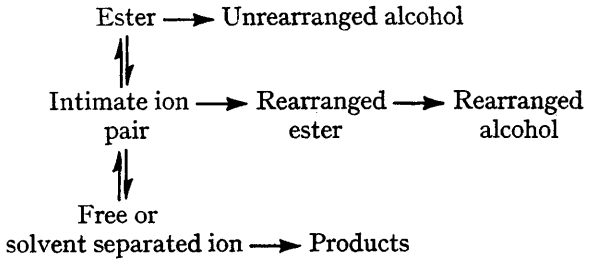
TABLE

Products of alkaline methanolysis of *cis*- and *trans*-2-pinanyl *p*-nitrobenzoates

		Products of bimolecular reaction as mole % of starting material		Products arising from: internal return as mole % of total unimolecular reaction		Composition of products arising from solvent separated ions (moles %)										
		cis-2-Pinanol (1)	*trans*-2-Pinanol (2)	Borneol (3)	α-Fenchol (4)	α-Pinene (5)	β-Pinene (6)	α-Fenchene (7)	Camphene (8)	Limonene (9)	Terpinolene (10)	α-Fenchyl methyl ether (11)	Bornyl methyl ether (12)	*cis*-2-Methylpinanyl ether (13)	*trans*-2-Methyl pinanyl ether (14)	α-Terpinyl methyl ether (15)
Ester	[NaOMe] M															
cis-2-Pinanyl *p*-nitrobenzoate (0·032 M)	0·033			3		33	10	1	1	4	3	3	2	25	3	13
	0·10	2		3		31	10	1	1	4	3	3	2	27	3	16
	0·30	12		3		32	10	1	1	4	3	3	2	28	3	16
	0·86	56		5		17	8	1	1	6	3	3	2	36	4	20
	3·0	94														
trans-2-Pinanyl *p*-nitrobenzoate (0·032 M)	0·033		9		34	2	5	1	1	5	3	7	2	30	15	23
	0·05		29		22	9	13	1	1	4	3	10	2	30	13	15
	0·10		42		22	10	13	1	1	4	2	10	2	29	13	13
	0·86		91		36	12	13	1	1	8	3	8	1	22	23	8
	3·0		94													

In addition to collapse to yield esters, the intimate ion pair can dissociate, probably by forming a solvent separated ion pair, which may yield methanolysis products either directly or *via* a 'free' ion. This ion can undergo considerable rearrangement to give, from either ester, a mixture of 11 products. These are reported in columns 5—15 of the table, each column giving the % of the 'free' ion reaction giving that product. In this way, it is possible to compare the products from each ester formed *via* a particular route.

The reactions are summarised as follows:



It is clear from the results in the Table that the stereochemistry of the ester is preserved in the intimate ion pairs. There is no evidence of interconversion of the esters, and formation of bornyl ester from *cis*-pinanyl ester, and α-fenchyl ester from *trans*-pinanyl ester are also completely specific. In the 'free' ion stage, however, some, though not all stereospecificity is lost. Thus, both esters give both *cis*- and *trans*-pinanyl methyl ethers, and both give bornyl and α-fenchyl methyl ethers, but there is no detectable formation of either isobornyl methyl ether or β-fenchyl methyl ether. We consider that this partial control of stereochemistry is incompatible with it being entirely controlled by ion pairs, and suggest that delocalised carbonium ions are responsible for the control. Since each ester gives both *cis*- and *trans*-pinanyl methyl ethers, we must propose an intermediate consisting of an interconverting pair of delocalised ions, as shown in Scheme 1.

On the basis of this scheme, we can provide a satisfactory explanation of the substitution products of the reaction. Initially, the *cis*-ester forms the ion (I), which can either be converted into (II), ring open to (III), or react with solvent. These processes compete, with reaction with solvent being slightly favoured at high concentrations of base. The *trans*-ester likewise forms the ion (II), which can either be converted into (I) or react with solvent; there is no evidence of a ring-opening reaction, which would yield a primary carbonium ion. Again, increasing base concentration favours products of reaction of the initially formed ion (II) over products of ions formed subsequently from (I).

The elimination products of ester solvolysis are less readily explained. A yield of 50% of olefins from the unimolecular solvolysis of the *cis*-ester in methanol was unexpected. Although the problem is specific to the *cis*-ester, we exclude the possibility that the main olefin, α-pinene, arises from a simultaneous *E*2 reaction, since the yield of this olefin decreases with increasing base concentration.

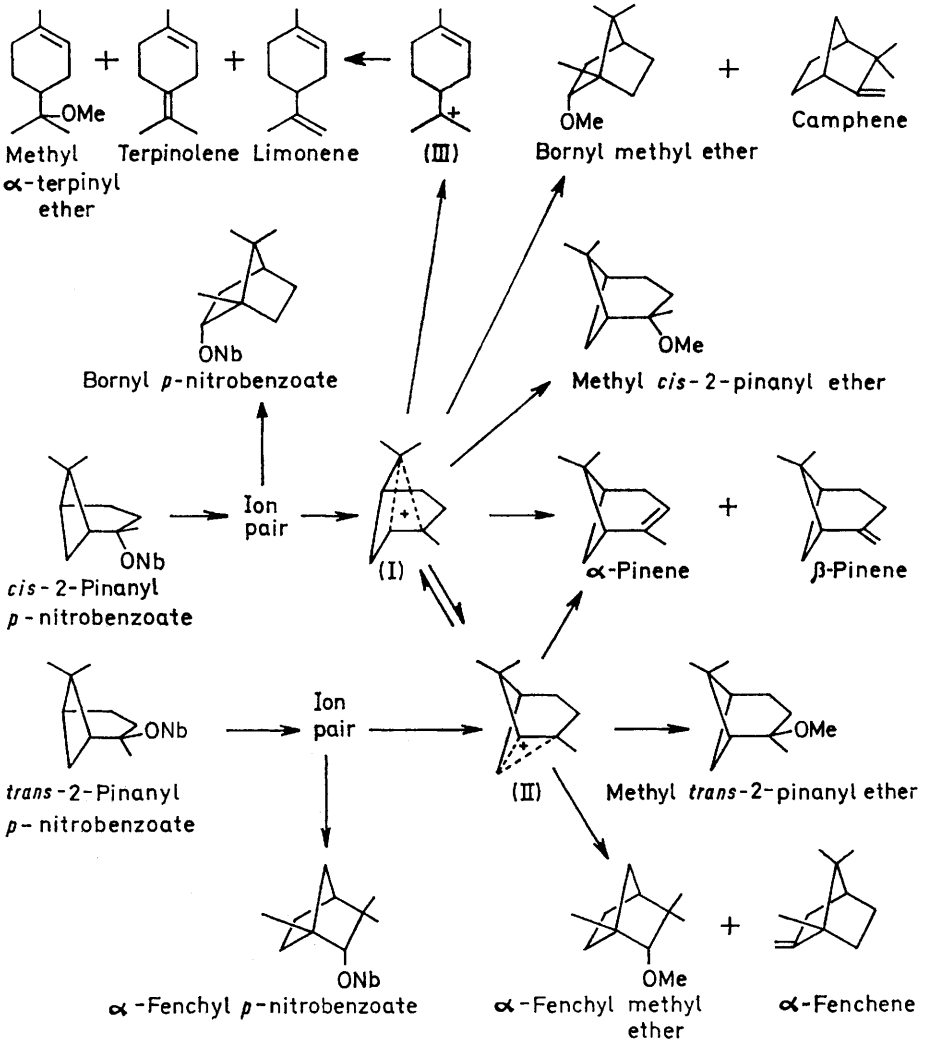
We suggest that at least part of the α-pinene arising from *cis*-2-pinanyl *p*-nitrobenzoate arises from elimination within the intimate ion pair. Eliminations of this type have been proposed [14,15] to account for variation in elimination products with leaving group in *E*1 reactions, and Winstein [16] has shown that these variations are readily observed in ethanol and acetic acid, though

[14] D. J. Cram and M. R. V. Sahyun, *J. Amer. Chem. Soc.*, 1963, **85**, 1257.

[15] P. S. Skell and W. L. Hall, *J. Amer. Chem. Soc.*, 1963, **85**, 2851.

[16] S. Winstein and M. Cocivera, *J. Amer. Chem. Soc.*, 1963, **85**, 1702.

unimportant in better ionising solvents. Sneen [17] has proposed a detailed analysis of a scheme in which elimination products can arise from the ion pair, the proton being removed by the counterion, and from the ' free ' ion, the proton being removed by base. In Part II, the extra steric hindrance of the *gem*-dimethyl bridge to the *p*-nitrobenzoate group in the *trans*-ester and its ion pair; we suggest, however, that a more likely cause is the difference in charge delocalisation between the ions (I) and (II). The extra methyl groups involved in de-



SCHEME 1 Products of methanolysis of pinanyl *p*-nitrobenzoates (ONb = *p*-nitrobenzoate)

it was shown [1] that this type of mechanism was important in the addition of acids to pinenes, the acid adding to give an ion pair, from which the counterion removed a proton in the reverse reaction to give 98% elimination in solvents of low dielectric constant.

Although the *trans*-ester appears to form an ion pair in the same way as the *cis*-, there is no evidence here that there is elimination taking place. In fact, we observe almost complete collapse of the ion pair to give α-fenchyl *p*-nitrobenzoate, this being formed (probably by coincidence) in almost exactly the same yield as α-pinene from the *cis*-ester. The reason for this difference may lie in localisation of charge in (I) presumably cause a greater delocalisation than in (II), in particular removing charge from the vicinity of the counterion, and hence reducing the possibility of collapse of the intimate ion pair.

The formation of α-pinene, β-pinene, camphene, and α-fenchene from the ' free ' ions (I) and (II) has been discussed in Part I of this series.[18]

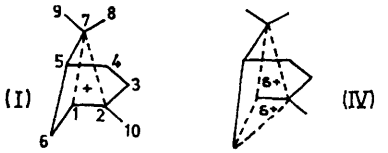
The ring opening reaction of (I) to yield (III) has also been discussed in Part I, and needs no further comment here, except to note that we have no explanation of the low yield of α-terpinyl methyl ether, particularly in comparison with the yield of limonene, which we have ob-

[17] R. A. Sneen and H. M. Robbins, *J. Amer. Chem. Soc.*, 1969, **91**, 3100.

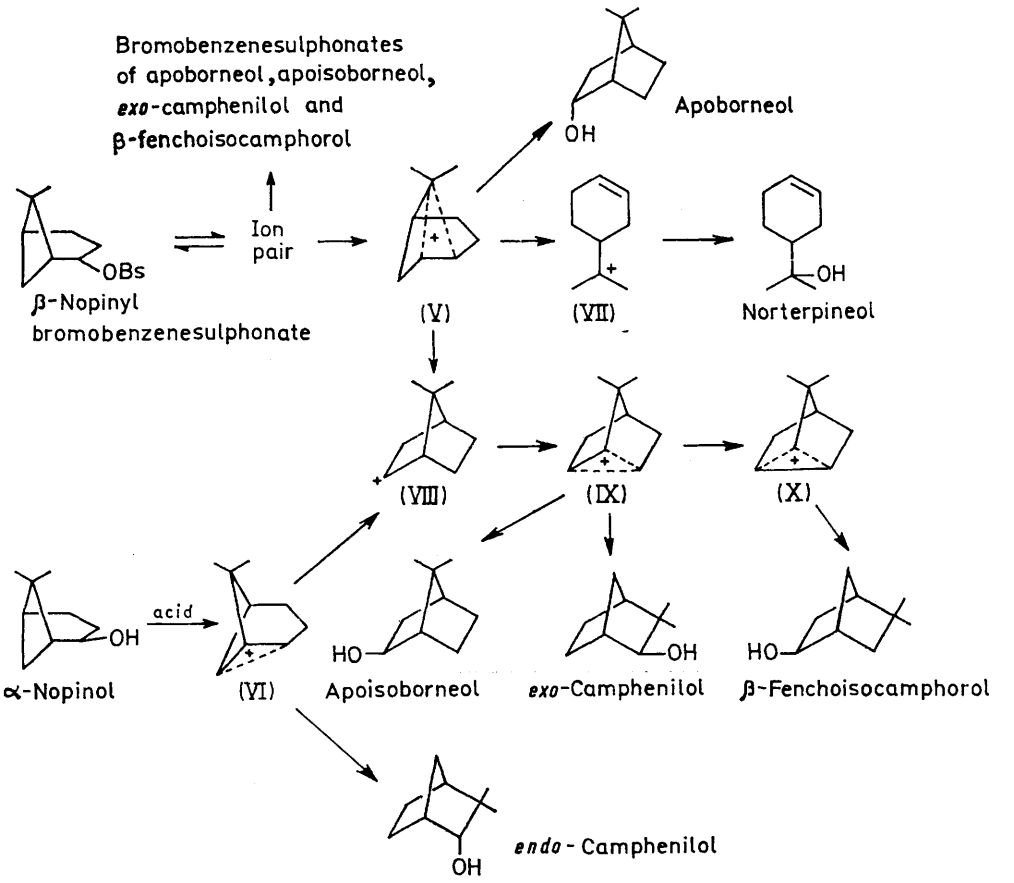
[18] Claudia M. Williams and D. Whittaker, *J. Chem. Soc.* (*B*), 1971, 668.

served from the *trans*-ester in the presence of 0·86M-methoxide ion.

Although interconversion of delocalised ions is uncommon, by considering the probable mechanisms of this reaction, we can see that the 2-pinanyl cations are particularly favourable to such a reaction. The two extreme forms of the ion (I) are a secondary ion and a tertiary ion. Since the methyl group on C-2 provides stabilisation of the latter relative to the former, the charge distribution over the delocalised ion is probably unsymmetrical, the electron deficiency being greater on C-2 than C-1.



We reject a classical ion as a possible transition state for the interconversion of two delocalised ions, as our kinetic data suggest that a charge developing on C-2 would be stabilised by interaction of the electrons of the C(1)–C(6) bond. We, therefore, suggest a structure such as (IV) as a transition state. We cannot exclude the possibility that both ions are slowly converted into (IV) which reacts with solvent to give products, but we have no means of distinguishing this from a mixture of (I) and (II), and hence cannot justify its postulation as an intermediate.



SCHEME 2 Products of reaction of the nopinols

By a closely related argument, the conversion of (II) into (I) can be explained.

The results of Winstein,[7] which are summarised in Scheme 2 can now be readily related to our own. Here, the two extreme forms of the ion are both secondary. In one case, there is a positive charge on C-2 and a bond from C-1 to C-7; in the other, a positive charge on C-1 and a bond from C-2 to C-7. Thus, although both ions are secondary, the structure of the former involves a 4-membered ring, while that of the latter involves only 5- and 6-membered rings. Clearly, the latter would be expected to be the more stable structure, so that we should expect (V), like (I), to have an unsymmetrical charge distribution, but in this case the greater part of the electron deficiency would be on C-1 rather than C-2. This is consistent with the small amount of nopinol derivatives among the solvolysis products of the ester.

Although Winstein interpreted his data on a mechanism involving a classical ion, formation of a transition state such as (XI) is also consistent with his data.

(XI)

Product differences between the two systems can now be readily understood. Since formation of (IX) from (V) corresponds to formation of (II) from (I) in our system, we should expect that the ion (VI) would not be formed from the β-nopinols. The expected product of this ion, *endo*-camphenilol, is not, in fact, observed among the products of β-nopinyl ester solvolysis. By similar reasoning we should expect that (VI) would be converted into (IX) directly, but not into (V), so that we should not expect, and do not get, apoborneol or norterpineol derivatives among the products of rearrangement of α-nopinol. Theoretically, we might predict interconversion of (V) and (VI) *via* (IX), but thermodynamic factors favour (IX) to such an extent that its formation does not appear to be reversible.[19]

Thus, despite the contrast in products from the two systems, the results are consistent with the initial formation of ions differing only in the presence of a methyl group. Two possible paths of rearrangement are then open to these ions, but the direction taken is controlled entirely by the methyl group, and the widely differing products are consistent with the same basic mechanism.

Recent work of Hückel [20] on the deamination of bornyl- and α-fenchyl-amines has provided further evidence to support the occurrence of the interconversion between (I) and (II). Deamination of bornylamine appears to proceed in part *via* (I), this route being favoured over the more common reaction route of borneol derivatives [21] when the leaving group is nitrogen, and ring-opening takes place, presumably *via* (III), to give monocyclic terpenes. However, deamination of α-fenchylamine gives similar monocyclic species, for which the most probable route of formation is amine ⟶ (II) ⟶ (I) ⟶ (III).

The agreement between theory and observations both in our work and Winstein's appears to justify our initial assumptions about the relative stabilities of the extreme forms of the ion (I). We must, therefore, conclude that the stability gain to a system by expansion of a 4-membered ring to a 5-membered ring is less than the stability gain by substituting a methyl group for hydrogen at a secondary carbonium ion centre.

[0/1969 *Received, November 18th*, 1970]

[19] P. Yates and R. J. Crawford, *J. Amer. Chem. Soc.*, 1966, **88**, 1561; C. J. Collins, V. F. Raaen, B. M. Benjamin, and I. T. Glover, *J. Amer. Chem. Soc.*, 1967, **89**, 3940; Y-i Lin and A. Nickon, *J. Amer. Chem. Soc.*, 1970, **92**, 3496.

[20] W. Hückel and H-J. Kern, *Annalen*, 1969, **728**, 49.

[21] P. Beltramé, C. A. Bunton, A. Dunlop, and D. Whittaker, *J. Chem. Soc.*, 1964, 658.