Rearrangements of Pinane Derivatives. Part IV.[1] Solvolysis of the Myrtanyl Toluene-*p*-sulphonates

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Methanolyses of the *cis*- and *trans*-myrtanyl toluene-p-sulphonates both proceed by part unimolecular and part bimolecular mechanisms. The unimolecular reactions proceed with synchronous shift of the C-2 hydrogen to give the pinan-2-yl cation. Formation of this ion by an indirect route removes the counterion from the vicinity of the carbonium ion centre, thus diminishing ion-pair effects on the reactions of the ion. Both isotope effects and product studies indicate that the bimolecular reaction proceeds by direct attack of the nucleophile on the substrate, rather than by attack on an ion-pair.

In Part III [1] of this series, we considered the solvolyses of the *cis*- and *trans*-pinan-2-yl *p*-nitrobenzoates in methanol containing sodium methoxide. The reaction showed a bimolecular component, but at low base concentrations proceeded mainly *via* a unimolecular process. Internal return from an intimate ion-pair gave some bornyl *p*-nitrobenzoate from *cis*-pinan-2-yl *p*-nitrobenzoate, and α-fenchyl *p*-nitrobenzoate from *trans*-pinan-2-yl *p*-nitrobenzoate. Solvolysis products were also obtained, but we were unable to discover whether they arose from a solvent-separated ion, in which case the *p*-nitrobenzoate ion continued to affect the course of reaction, or from a 'free' (*i.e.* solvated only by solvent molecules) ion, the *p*-nitrobenzoate ion being too far away to influence behaviour.

Evidence of ion pairing has also been observed by Winstein [2] in the study of nopinyl bromobenzenesulphonates, in which reaction extensive return from an intimate ion-pair to rearranged bromobenzenesulphonates was observed. Solvolysis products again offered no clue as to whether they arose from a solvent-separated ion pair or a free ion.

An obvious approach to the question of influence of counter-ion on solvolysis products would be variation of the leaving group. However, in the pinanyl and nopinyl systems, which are unusually prone to ion-pair effects, the lability of the systems makes synthesis of a series of esters with widely differing leaving groups impractical. To date, only one pair of esters has been studied in each of the pinanyl,[1] nopinyl,[2] and norpinyl [3] systems, and skeletal changes between these systems make comparisons difficult. We therefore sought to study the problem by reaction of a pinanyl ester in which the ester group is on the neighbouring carbon atom to the C-2 position which we wish to study. Generation of a carbonium ion by hydride shift should give an ion in which the counter-ion is already remote, and should then readily separate from the carbonium ion. We chose the myrtanyl esters, since solvolysis of a primary ester, provided it does not involve a bimolecular reaction, should give the maximum driving force to a hydride shift to yield a tertiary carbonium ion. In a preliminary communication,[4] we have shown that reaction does involve generation of a carbonium ion at C-2, and have shown that the ion is probably delocalised.

EXPERIMENTAL

Materials.—The β-pinene used in preparation of materials was purified by distillation through a helix-packed column at 165—166° at 760 mm.

cis-*Myrtanyl Toluene*-p-*sulphonate.*—*cis*-Myrtanol, prepared by the method of Brown,[5] had b.p. 81—83° at 0·6 mm. The n.m.r. spectrum showed a doublet, $J = 7{\cdot}5$ Hz at τ 6·40 due to the $-CH_2-OH$ protons. Reaction with toluene-*p*-sulphonyl chloride in pyridine for 24 hr.[6] gave cis-*myrtanyl toluene*-p-*sulphonate*, as white crystals, recrystallised from n-hexane to m.p. 75·5—76° (Found: C, 66·4; H, 7·8; S, 10·6. $C_{17}H_{24}O_3S$ requires C, 66·2; H, 7·8; S, 10·4%).

[1] Part III, J. R. Salmon and D. Whittaker, *J. Chem. Soc.*, (*B*), 1971, 1249.
[2] S. Winstein and E. C. Friedrich, *J. Amer. Chem. Soc.*, 1964, **86**, 2721.
[3] W. Kirmse and R. Siegfried, *J. Amer. Chem. Soc.*, 1968, **90**, 6504.
[4] J. R. Salmon and D. Whittaker, *Chem. Comm.*, 1967, 491.
[5] H. C. Brown and G. Zweifel, *J. Amer. Chem. Soc.*, 1964, **86**, 393.
[6] R. Tipson, *J. Org. Chem.*, 1944, **9**, 235.

Repetition of the above preparation using sodium borodeuteride in the alcohol synthesis gave an alcohol similar except that the $-CH_2-OH$ protons now gave a single peak due to replacement of the C-2 hydrogen by deuterium; this part of the n.m.r. spectrum was not affected by esterification.

trans-*Myrtanyl Toluene*-p-*sulphonate.*—*trans*-Myrtanol, prepared by the method of Brown [7] had b.p. 81—83° at 0·6 mm. The n.m.r. spectrum showed a doublet, $J = 7{\cdot}5$ Hz at τ 6·58 due to the $-CH_2-OH$ protons. Reaction as above yielded trans-*myrtanyl toluene*-p-*sulphonate*, m.p. 50—50·5° (Found: C, 66·5; H, 7·7; S, 10·7. $C_{17}H_{24}O_3S$ requires C, 66·2; H, 7·8; S, 10·4%).

Repetition of the preparation using sodium borodeuteride instead of sodium borohydride again gave a similar alcohol, except that the $-CH_2-OH$ protons gave a single peak due to deuterium on C-2. The position of the label was not affected by conversion into the toluene-*p*-sulphonate.

Samples of the methyl ethers of *cis*- and *trans*-myrtanol were prepared by reaction of the sodium compound of the alcohol with methyl iodide. Both were liquids, and were purified by preparative scale g.l.c. Authentic samples of other products were prepared as described previously.[1]

Kinetic Procedure.—The solvent used throughout this work was methanol, purified by the method of Vogel.[8]

All kinetic measurements were carried out at 85·0 °C. Solutions of the ester, 0·032M, in methanol plus the appropriate amount of sodium methoxide were sealed in Pyrex tubes at room temperature. The toluene-*p*-sulphonic acid liberated in neutral reactions was titrated with sodium hydroxide solution, using Bromothymol Blue as indicator; for reactions in basic solution the excess base was titrated with hydrochloric acid, using Bromothymol Blue as indicator.

Product studies were carried out under similar conditions and then extracted with pentane; the extract was washed, dried, and the pentane removed; the product was analysed by g.l.c. using a 50-ft. capillary column coated with S.E. 33 at 74 °C. Products were identified by i.r. spectra of samples obtained by preparative scale g.l.c., using a 6-ft. × $\frac{3}{8}$ in. column, packed with 60—80 mesh Celite coated with 20% Carbowax 400 at 130 °C.

RESULTS AND DISCUSSION

Kinetic data on the *cis*- and *trans*-myrtanyl toluene-*p*-sulphonates in methanol at 85° showed the reactions to be first order; in the presence of base, the rate increased and the reactions deviated from first-order kinetics, becoming intermediate in behaviour between first order and second order. The first-order rate constants, recorded over the initial part of the reaction where necessary, are recorded in Table 1. A plot of the rates at low base concentration against base concentration gave straight lines, whose intercepts were the rate constants for the unimolecular reaction, and from whose slopes the bimolecular rates could be obtained.

These were as follows: for the *cis*-ester, $k_1 = 1{\cdot}50 \times 10^{-5}$ sec.$^{-1}$ and $k_2 = 5{\cdot}7 \times 10^{-5}$ l. mole^{-1} sec.$^{-1}$; for the *trans*-ester, $k_1 = 0{\cdot}64 \times 10^{-5}$ sec.$^{-1}$ and $k_2 = 36{\cdot}8 \times 10^{-5}$ l. mole^{-1} sec.$^{-1}$. At higher base concentrations, the rate of reaction of the *cis*-ester increases faster than would be expected on this scheme; that of the *trans*-ester does not.

The rate constants show that the *cis*-ester, in which there is some steric interaction between the *gem*-dimethyl bridge and the toluene-*p*-sulphonate group, reacts more slowly by the bimolecular route and more rapidly by the unimolecular route than does the less-hindered *trans*-ester, as would be expected.

TABLE 1

Rates of solvolyses of *cis*- and *trans*-myrtanyl toluene-*p*-sulphonates in methanol at 85°

Ester (0·032M)	[NaOMe] (M)	$k_1 \times 10^5$ sec.$^{-1}$
cis-Myrtanyl toluene-*p*-sulphonate	0	1·50
	0·033	1·66
	0·05	1·77
	0·10	2·07
	0·88	17·3
cis-[2-$^2H_1$]Myrtanyl toluene-*p*-sulphonate	0	0·78
	0·033	0·93
trans-Myrtanyl toluene-*p*-sulphonate	0	0·58
	0·05	1·86
	0·10	4·26
	0·88	34
trans-[2-$^2H_1$]Myrtanyl toluene-*p*-sulphonate	0	0·46
	0·10	4·29

The solvolysis products, summarised in Table 2, are consistent with the mechanisms outlined above. Reaction of the *cis*-ester gives, with increasing base concentration, increasing amounts of β-pinene, the expected product of *E*2 elimination. This reaction almost certainly causes the rapid increase of rate of reaction of the ester at high base concentration. This reaction does not take place with the *trans*-ester. We suggest that this is because of steric hindrance by the *gem*-dimethyl group to approach of base to the hydrogen on the β-carbon atom. The β-pinene is almost certainly not entirely a product of *E*2 elimination, as it could well arise in low yields from the unimolecular reaction.

Both reactions yield the corresponding myrtanyl methyl ethers, which would be the expected products of bimolecular reaction. On the basis of the data given above, we calculate that the composition of products from the *cis*-ester in 0·94M-base would be 30% from S_N2 reaction, 7% from S_N1 and 53% from *E*2, corresponding well with the measured values of 30, 5, and 55%. A similar calculation for the *trans*-ester suggests 98% of S_N2 product, as observed.

The rest of the reaction products suggest extensive reaction by generation of a carbonium ion at C-2. This could arise by a hydride shift either during or following ionisation, the former being the more probable as it does not involve preliminary formation of a primary carbonium ion. We sought to differentiate between the possibilities by replacing the hydrogen on C-2 with a deuterium; participation of the C-2 hydrogen in ionisation of the toluene-*p*-sulphonate should be detected by an unusually large β-deuterium isotope effect.

[7] H. C. Brown and G. Zweifel, *J. Amer. Chem. Soc.*, 1961, **83**, 2544.

[8] A. I. Vogel, ' A Text-book of Practical Organic Chemistry,' Longmans, London, 1951, 2nd edn., p. 168.

Typical examples of β-deuterium isotope effects for reactions in which a 1,2-hydride shift is believed to accompany departure of a toluene-*p*-sulphonate group are k_H/k_D of 1·85 for the *erythro*-form and 1·72 for the *threo*-form of 3-cyclohexyl-2-butyltoluene-*p*-sulphonate [9] and, for 3-methyl-2-butyltoluene-*p*-sulphonate,[10] k_H/k_D values of 2·14 in aqueous 80% ethanol, 2·26 in acetic acid, and 2·24 in formic acid. These are in good agreement with the value of $k_H/k_D = 1·9$ which has been calculated on the basis of a three-centre symmetrical transition-state.[11]

We found that in neutral methanol, the β-deuterium isotope effect on the solvolysis of *cis*-myrtanyl toluene-*p*-sulphonate was $k_H/k_D = 1·92$; in the presence of 0·033M-sodium methoxide, it fell to 1·79. Comparison of calculated values of k_1 and k_2 with those given earlier for the hydrogen compounds indicates that for the unimolecular reaction $k_H/k_D = 1·92$ while for the bimolecular reaction $k_H/k_D = 1·0$. The isotope effect on the unimolecular reaction is clearly within the region to be expected for participation of hydrogen in the ionisation. The isotope effect on the *trans*-ester in neutral solutions where the reaction is dominantly S_N1, is 1·26, which, though much less than that observed in the *cis*-ester, is still consistent with hydride transfer during ionisation, being much greater than the normal β-deuterium isotope effects. The lower effect may be a result of steric hindrance from the *gem*-dimethyl group to the hydride transfer. However, reaction in the presence of 0·1M-sodium methoxide, which product studies indicate to be 90% bimolecular reaction shows the isotope effect to be 1·0. This agrees well with the result obtained on the *cis*-ester, and has the advantage of being measured directly. The results clearly show that the unimolecular reaction involves hydride transfer during ionisation, and is not consistent with formation of a primary carbonium ion.

We thus have two isomers whose substitution reactions show simultaneous unimolecular and bimolecular components, the former proceeding with a synchronous hydride transfer. The system is particularly well suited to test the suggestion of Sneen [12] that bimolecular reactions may proceed by rate-determining attack of a nucleophile on an intimate ion-pair, rather than on an un-ionised substrate. This suggestion would have the effect of unifying mechanisms S_N1 and S_N2, since both reactions would consist of preliminary ionisation to an ion-pair, which could spontaneously decompose (S_N1) or be attacked by a nucleophile (S_N2). We have already shown that ionisation of both *cis*- and *trans*-myrtanyl toluene-*p*-sulphonates is accompanied by a shift of the C-2 hydrogen, generating a carbonium ion centre at C-2. There is no evidence of this hydride shift being reversible, as the stereospecificity of the bimolecular reactions precludes any isomerisation of the esters. If the bimolecular reaction involved nucleophilic attack on an ion-pair, it would have to proceed at C-2 giving products of reaction at that atom, and would show an isotope effect similar to that observed in the unimolecular reaction.

The data given above contradict both predictions.

Reactions of *cis*- and *trans*-myrtanyl toluene-*p*-sulphonates give the appropriate myrtanyl methyl ethers by reaction at C-10 in yields which correspond to calculated rate constants for the S_N2 reaction. The isotope effects observed on the unimolecular reactions are not paralleled in the bimolecular reactions. Clearly our data are not consistent with the S_N2 reactions involving nucleophilic attack on an ion-pair.

Alternatively, it could be suggested that the rate-determining step of ionisation was separation of an intimate ion-pair. Formation of an ion-pair at C-10 could then be followed by spontaneous ionisation,

TABLE 2

Products of alkaline methanolysis of *cis*- and *trans*-myrtanyl toluene-*p*-sulphonates

Ester	[NaOMe] (*M*)	Products of bimolecular reaction (moles %)			Composition of products arising from carbonium ion at C-2 (moles %)										
		β-Pinene	*cis*-Myrtanyl methyl ether	*trans*-Myrtanyl methyl ether	Unknown	α-Pinene	α-Fenchene	Camphene	Limonene	Terpinolene	α-Fenchyl methyl ether	Bornyl methyl ether	*trans*-Pinan-2-yl methyl ether	*cis*-Pinan-2-yl methyl ether	α-Terpinyl methyl ether
cis-Myrtanyl toluene-*p*-sulphonate (0·032M)	0·033	19	6		1	3	7	1	8	6	6	2	7	25	35
	0·30	39	20		2	4	7	1	10	6	6	2	6	25	31
	0·67	48	30		2	6	7	2	11	6	5	2	6	26	28
	0·94	55	30		3	9	8	1	10	5	5	2	5	28	23
	3·0	52	46												
trans-Myrtanyl toluene-*p*-sulphonate (0·032M)	0·033	6		38		6	1	2	8	7	5	3	4	27	36
	0·049	2		78		6	1	2	8	7	5	3	4	27	36
	0·099	2		90		7	1	3	8	6	5	3	5	27	35
	0·30	1		95		7	2	3	9	6	5	3	5	26	33
	0·67	1		97		8	2	4	10	5	5	3	6	27	30
	0·94	1		98											
	3·0	1		99											
cis-Pinan-2-yl *p*-nitrobenzoate (0·032M)	0·033					33 *		1	4	3	3	2	3	25	13
trans-Pinan-2-yl *p*-nitrobenzoate (0·032M)	0·033					2	1	1	5	3	7	2	15	30	23

* Formed mainly from elimination within an intimate ion-pair.

[9] D. J. Cram and J. Tadaniev, *J. Amer. Chem. Soc.*, 1959, **81**, 2737.

[10] S. Winstein and J. Takahashi, *Tetrahedron*, 1958, **2**, 316.

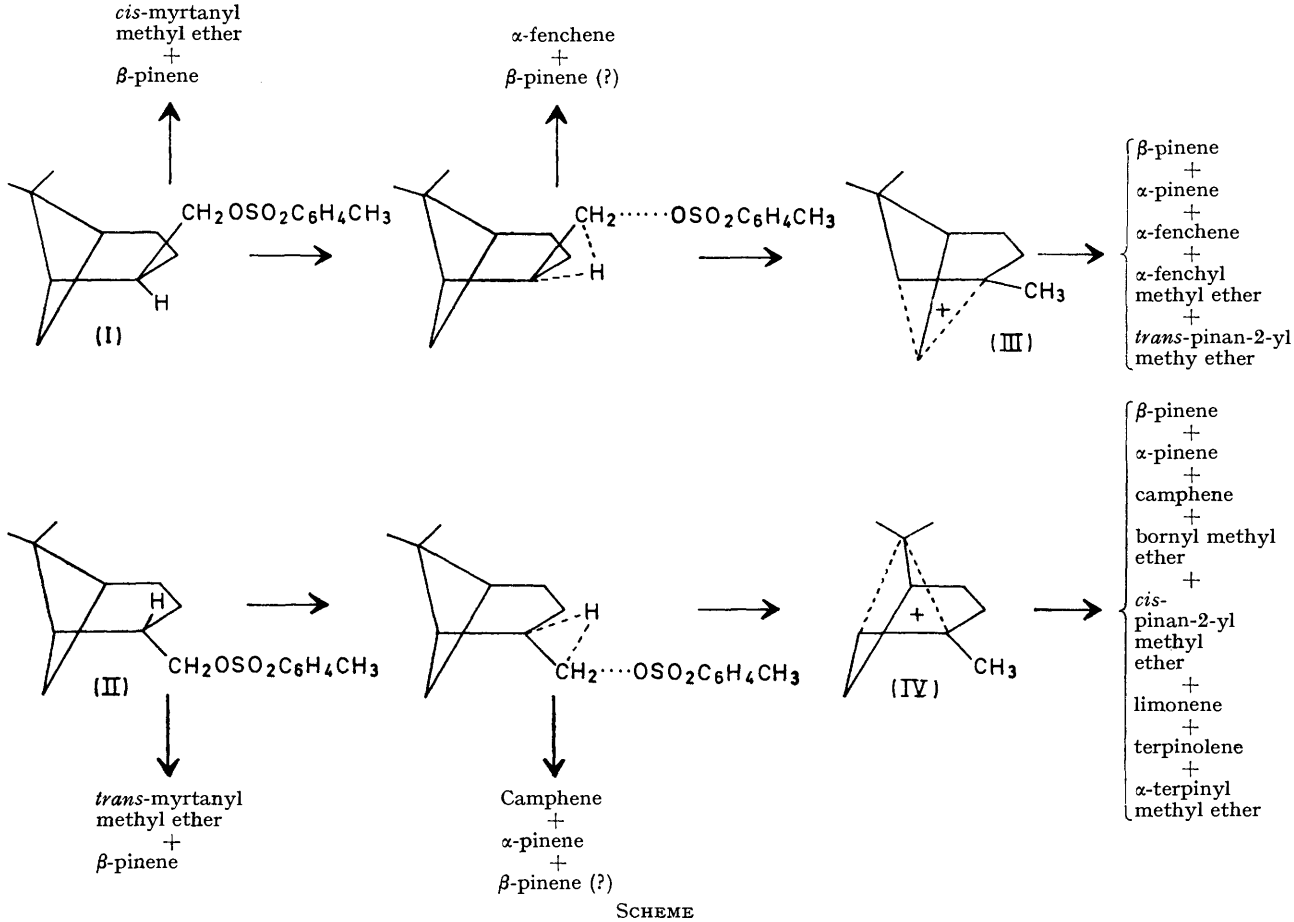
[11] R. A. More O'Ferrall, *J. Chem. Soc.* (*B*), 1970, 785.

[12] R. A. Sneen and J. W. Larsen, *J. Amer. Chem. Soc.*, 1969, **91**, 362; R. A. Sneen and J. W. Larsen, *J. Amer. Chem. Soc.*, 1969, **91**, 6031.

involving hydride transfer, or nucleophilic attack. However, this appears unlikely in the light of known reactions in which ion-pair formation involves neighbouring-group participation,[13] and the lack of solvent influence on the isotope effect.[10]

We conclude that in this instance bimolecular substitution involves attack on the un-ionised substrate, although it should be pointed out that methanolysis of a primary alkyl toluene-*p*-sulphonate is a particularly unfavourable system for observation of the ion-pair counterion to C-2, we should not expect any pinanyl ester, but would expect bornyl and α-fenchyl esters. We prepared one of the main products of bornyl toluene-*p*-sulphonate methanolysis,[14] camphene hydrate methyl ether, and showed it to be absent from our solvolysis products. Clearly, we have no products of esters arising from internal return from an ion-pair at C-2.

The products reveal some differences in yields of camphene, α-fenchene, and α-pinene between the two systems, which we suggest may result from elimination



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mechanism, so that this could prove to be an exceptional rather than a general case.

The unimolecular reaction, like the bimolecular reaction, shows no evidence of being influenced by ion-pair formation.

The products of solvolysis of the myrtanyl esters, given in Table 2, show that rearrangement resulting from ion-pair return to a rearranged ester is absent. In Part III we showed that pinan-2-yl esters solvolysed *via* an intimate ion-pair, return from which gave bornyl and α-fenchyl esters. If hydride shift during ionisation of the myrtanyl esters were accompanied by shift of the by removal of a proton from the ion by the departing toluene-*p*-sulphonate group. We have previously suggested [15] that the first step in formation of camphene, α-fenchene, and β-pinene from the pinan-2-yl ions is removal of a proton from C-10. Extension of this theory to reactions of the myrtanyl esters suggests that removal of a proton from C-10 by the departing toluene-*p*-sulphonate group, either the C-2 hydrogen during transfer or a C-10 hydrogen (yields of olefins are too small to permit isolation of sufficient material from the deuteriated ester solvolysis to check this point) would give rise to α-fenchene from the *cis*-ester and camphene from the *trans*-ester, as observed, the mechanism being

[13] S. Winstein and D. Trifan, *J. Amer. Chem. Soc.*, 1951, **74**, 1147, 1154.

[14] W. Huckel, C. M. Jennewein, H. J. Kern, and O. Vogt, *Annalen*, 1968, **719**, 157.

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

essentially an α-elimination. It is probable[15] that elimination *via* this route also gives some β-pinene from both myrtanyl esters, but this is obscured by formation of β-pinene by other routes. A further elimination product can be formed in this way from the *trans*-ester (II) since the departing anion must pass close to C-3, and can hence remove a proton from this carbon atom to initiate an elimination process leading to α-pinene.[15] Steric hindrance of the *gem*-dimethyl group and unfavourable substrate conformation make this process less likely in the *cis*-ester, so that the yield of α-pinene from the trans-ester exceeds that from the *cis*.

Other solvolysis products from the two myrtanyl esters are almost identical, and are consistent with formation of an equilibrating pair of delocalised ions, (III) and (IV), which we discussed in Part III. Evidence from the eliminations discussed above, however, shows that it is the *cis*-ester which gives rise to (III) and the *trans*- to (IV); clearly the direction of ring expansion is controlled by steric factors, as this *cis*-ester would have been expected to give (IV) if the ring expansion had assisted the hydride transfer reaction. It probably does not do so because the C-2 hydride moves towards C-10 at a shallow angle which is unsuitably aligned for assistance from ring expansion. Ring expansion does however, occur more rapidly than the attainment of planarity by C-2.

The data in Table 2 contrast with results obtained on the pinan-2-yl *p*-nitrobenzoates, in that the ratio of *cis*- to *trans*-pinan-2-yl methyl ether is almost constant with increasing base concentration. Clearly, the equilibration of (III) and (IV) is more rapid in this case, which is consistent with the absence of the stabilising factor of a solvent separated counterion. It is probably the difference between a solvent separated ion-pair and a solvent-solvated ion which is also responsible for the large increase, by a factor of almost 2, in the yield of ring-opened products. This is consistent with the absence of ring-opened products from intimate ion-pairs formed during solvolysis,[1] although ring opening can occur when the ion-pair has a long life.[16]

We conclude that we have obtained a solvent-solvated ion, and that it shows no qualitative differences from the solvent separated ion-pair obtained earlier. The quantitative differences observed are considerable, however, and can be considered in terms of a speeding up of rearrangements of the ion relative to the rate of capture by an external nucleophile.

[16] C. M. Williams and D. Whittaker, *J. Chem. Soc.* (*B*), 1971, 672.

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