

[1,4] and [5,5] Thermal Sigmatropic Rearrangements of 2-Pentadienyloxy pyridine *N*-Oxides

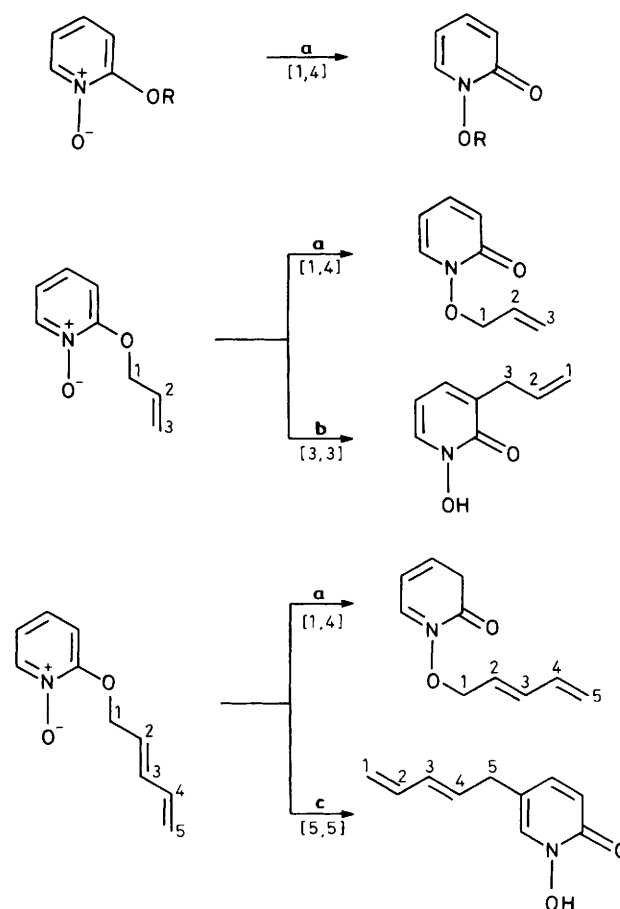
David Alker, W. David Ollis,* and Hooshang Shahriari-Zavareh
Department of Chemistry, The University, Sheffield S3 7HF

2-Pentadienyloxy pyridine *N*-oxides (**3**) are smoothly transformed on heating into *N*-pentadienyloxy-2-pyridones (**4**) and *N*-hydroxy-5-pentadienyl-2-pyridones (**5**). These reactions are shown to be regiospecific and are believed to proceed in a concerted fashion. The [5,5] sigmatropic rearrangement (**3**)→(**5**) takes place under moderate conditions and in good yield, although it presumably involves a ten-membered cyclic transition state.

Our general interest in the mechanism of sigmatropic rearrangements involving anionic or dipolar precursors has promoted a detailed examination^{1,2} of the thermal transformation of 2-alkoxy pyridine *N*-oxides into *N*-alkoxy-2-pyridones (Scheme 1; reaction **a**). This reaction is a [1,4] sigmatropic rearrangement and was first described by Dinan and Tieckelmann in 1964.³ At first sight, the occurrence of this reaction apparently conflicts with the generalisation put forward by Eschenmoser in 1970⁴ that endocyclic intramolecular nucleophilic substitutions would be inhibited. This generalisation was based upon the perception that there would be a stereoelectronic requirement for collinearity of three atoms when they participate in a nucleophilic substitution with inversion, but that this collinearity would be incompatible with the geometrical constraints imposed by an endocyclic transition state. The occurrence of reaction **a** (Scheme 1) was therefore of considerable interest but the offending reaction was satisfactorily interpreted in terms of orbital symmetry opportunities which enabled reaction **a** to proceed in a concerted fashion. This involved additional participation by the π -system of the pyridine *N*-oxide ring and reaction **a** could then be regarded as a 6-electron [1s, 4s] process requiring retention of configuration at the terminus of the migrating R group.⁴ Persuasive experimental support for this view was provided by the detailed investigation reported by Schöllkopf and Hoppe.⁵ However, further experimental enquiry^{6,7} has suggested that reaction **a** (Scheme 1) may proceed either by a concerted process involving a cyclic transition state, or by a non-concerted process involving a radical pair intermediate. It has also been suggested⁵ that preference for one of these two different mechanistic pathways could well be determined by the nature of the migrating R group.

In this situation, the allyl group could well be a highly informative mechanistic probe. Its participation in a concerted process would be regiospecific, whereas its participation as a free radical in a radical pair process would lead to scrambling. Thus, by the use of specifically labelled allyl substituents, it would be possible to distinguish between concerted pericyclic reactions or non-concerted radical pair processes. The allyl group needs to be specifically labelled by substitution either with deuterium or methyl groups. Using these methods, we have shown^{1,2} that 2-allyloxy pyridine *N*-oxides are smoothly transformed by [1,4] sigmatropic rearrangements (Scheme 1; reaction **a**) into *N*-allyloxy-2-pyridones, and by [3,3] sigmatropic rearrangements (Scheme 1; reaction **b**) into 3-allyl-*N*-hydroxy-2-pyridones. The factors influencing the periselectivity between [1,4] and [3,3] sigmatropic rearrangement of 2-allyloxy pyridine *N*-oxides have been closely examined.¹ Complete regiospecificity has been observed² in the [1,4] and in the [3,3] sigmatropic rearrangement of 2-allyloxy pyridine *N*-oxides.

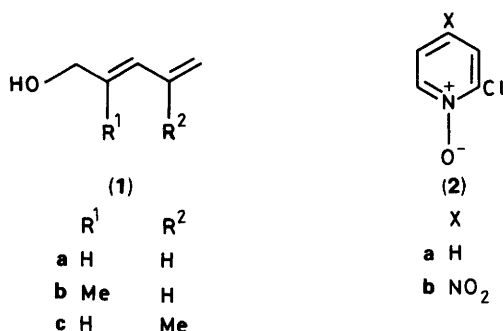
These results^{1,2} clearly indicate that the [1,4] and the [3,3] sigmatropic rearrangements of 2-allyloxy pyridine *N*-oxides are concerted and involve five- and six-membered cyclic transition states, respectively.



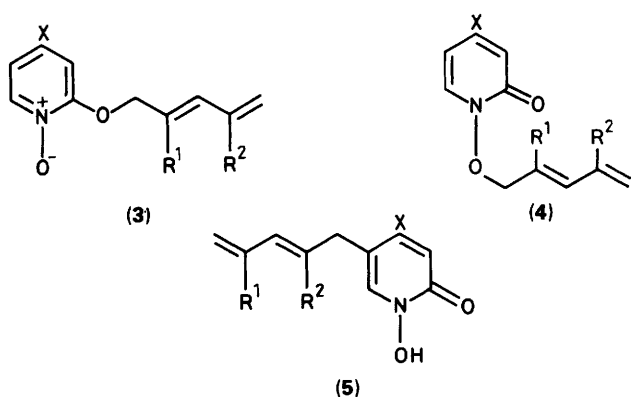
Scheme 1. Sigmatropic rearrangements of 2-alkoxy-, 2-allyloxy-, and 2-[(2*E*)-penta-2,4-dienyloxy]-pyridine *N*-oxides

We have also been rewarded by the use of penta-2,4-dienyl groups as mechanistic probes. This led to the discovery of several new types of higher order sigmatropic rearrangements including (i) the [5,4] sigmatropic rearrangement exhibited by allyl(pentadienyl)ammonium ylides at room temperature,⁸ (ii) the [5,4] sigmatropic rearrangement shown by *N*-pentadienyl-2-oxyanilinium ylides at 0 °C,⁹ (iii) the [5,2] sigmatropic

rearrangement shown by pentadienylammonioamidates,¹⁰ and (iv) the [5,2] sigmatropic rearrangement of pentadienylammonium ylides.¹¹ Furthermore, using appropriately substituted pentadienyl derivatives, it was possible to investigate the periselectivity between [1,4] and [5,4] sigmatropic rearrangements associated with reactions (i) and (ii) and the periselectivity between [1,2], [3,2], and [5,2] sigmatropic rearrangements for the reactions (iii) and (iv). This experience persuaded us to examine the thermal transformation of 2-[(2*E*)-penta-2,4-dienyloxy]pyridine *N*-oxides (3). The results are briefly summarised in Scheme 1 (reactions a and c). It will be appreciated that these results raise some interesting questions since they are not entirely in accord with our expectations.



Reaction between the (2*E*)-penta-2,4-dienols (1a–c) and sodium hydride in tetrahydrofuran followed by the addition of 2-chloropyridine *N*-oxide (2a) yielded the corresponding 2-[(2*E*)-penta-2,4-dienyloxy]pyridine *N*-oxides (3a–c). Thermal rearrangement of the 2-[(2*E*)-penta-2,4-dienyloxy]pyridine *N*-oxides (3a–c) occurred when they were heated (100 °C; 90 min) in dimethylformamide. In each case only two products were formed: they were identified as the corresponding *N*-[(2*E*)-penta-2,4-dienyloxy]-2-pyridones (4a–c; yields 27, 43, and 42%, respectively) and the corresponding *N*-hydroxy-5-[(2*E*)-penta-2,4-dienyl]-2-pyridones (5a–c; yields 65, 55, and 55%, respectively). The total yields of the products (4) and (5) are almost quantitative.

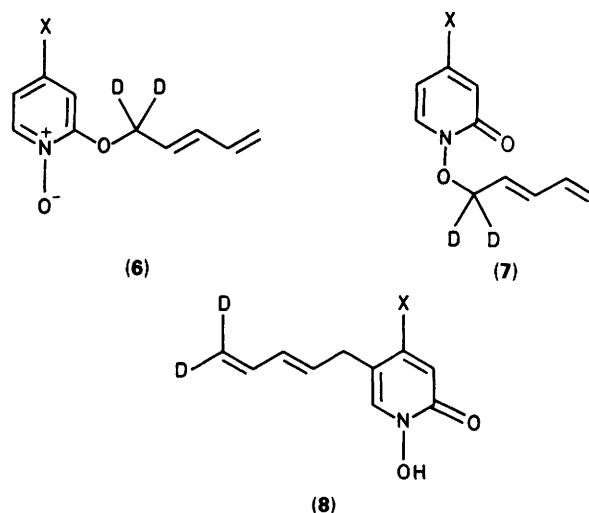


In formulae (3), (4), and (5):

| | R ¹ | R ² | X |
|---|----------------|----------------|-----------------|
| a | H | H | H |
| b | Me | H | H |
| c | H | Me | H |
| d | H | H | NO ₂ |

Various mechanistic possibilities could be considered for the transformation (3)→(4) + (5), but the most attractive hypothesis was that the products (4) are produced by [1,4] sigmatropic rearrangement and the products (5) by [5,5]

sigmatropic rearrangement. This proposal was put to the test by examining the thermal rearrangement of the specifically labelled 1,1-dideuteriopentadienyl derivative (6a). Its thermal rearrangement was carried out in exactly the same manner as that of the undeuteriated compound (3a). This yielded *N*-[(2*E*)-1,1-dideuteriopenta-2,4-dienyloxy]-2-pyridone (7a) (50% yield) and *N*-hydroxy-5-[(2*E*)-5,5-dideuteriopenta-2,4-dienyl]-2-pyridone (8a) (44% yield). It was established by examination of the mass spectra and NMR spectra of the products that the rearrangement (6a)→(7a) + (8a) proceeded regiospecifically with complete retention of deuterium. This demonstrated that the rearrangements (3)→(4) and (6)→(7) proceeds solely by a concerted [1,4] sigmatropic rearrangement and that a dissociation–recombination mechanism involving a radical pair intermediate could not be involved. It also firmly established that the rearrangements (3)→(5) and (6)→(8) proceeds solely by a concerted [5,5] sigmatropic rearrangement involving a ten-membered cyclic transition state. This is a remarkable result. In principle, the generation of the [5,5] sigmatropic rearrangement product could have involved a sequence of two [3,3] sigmatropic rearrangements. However, this possibility is definitely excluded because such a sequence of two [3,3] sigmatropic rearrangements would necessarily have given a product (8) in which the deuterium label was equally distributed between position 1 and position 5 of the penta-2,4-dienyl group. It is particularly noteworthy that the thermal rearrangement of 2-allyloxypyridine *N*-oxides^{1,2} does give rise to the products of [3,3] sigmatropic rearrangements (Scheme 1; reaction b), whereas 2-pentadienyloxypyridine *N*-oxides (3) when heated do not participate in [3,3] sigmatropic rearrangements to give either intermediates or isolable products. This exclusive periselectivity for a [5,5] in preference to a [3,3] sigmatropic rearrangement is even more striking when it is recalled that the thermal rearrangement of (2*E*)-penta-2,4-dienyl phenyl ether (9a) gives two products (10a) and (11a) formed by concurrent [3,3] and [5,5] sigmatropic rearrangements.^{12–14}

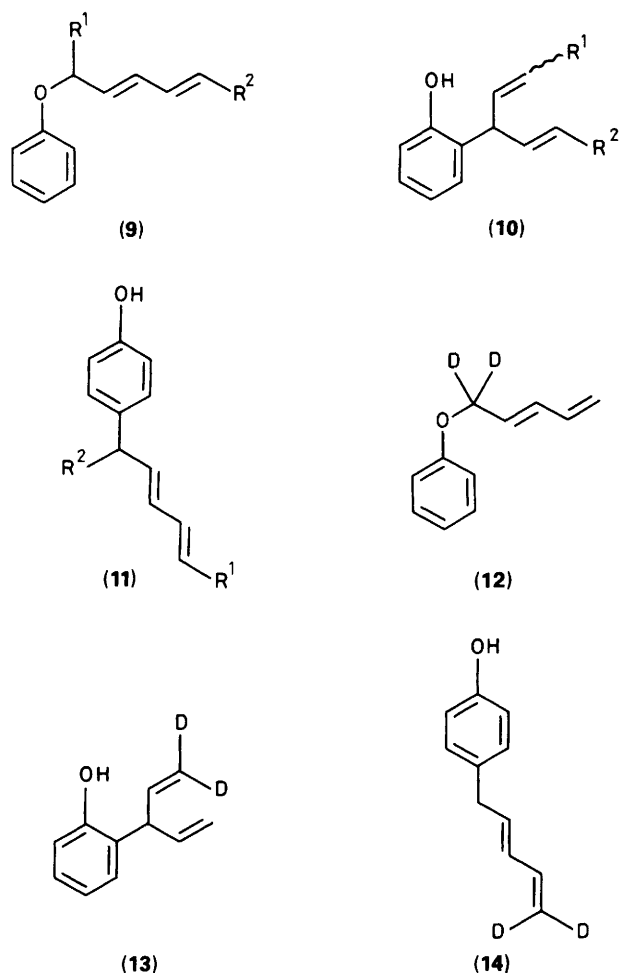


In formulae (6), (7), and (8): a, X = H; b, X = NO₂

The influence of a 4-nitro substituent upon the thermal rearrangement of 2-pentadienyloxypyridine *N*-oxides has been superficially examined. The attempted synthesis of the compound (3d) did not lead to its isolation, but its [1,4] sigmatropic rearrangement product (4d) was isolated instead. Similarly, the attempted synthesis of the 1,1-dideuteriopenta-2,4-dienyl derivative (6b) led only to the isolation of its [1,4] sigmatropic rearrangement product (7b). It is noteworthy that, in these two cases, the presence of the 4-nitro substituent apparently

inhibited the formation of the [5,5] sigmatropic rearrangement product (**8b**). This result provides an interesting contrast with the thermal rearrangement of 2-allyloxy-4-nitropyridine *N*-oxide when the formation of products from the [1,4] (46% yield) as well as the [3,3] sigmatropic rearrangement (50% yield) are observed.¹

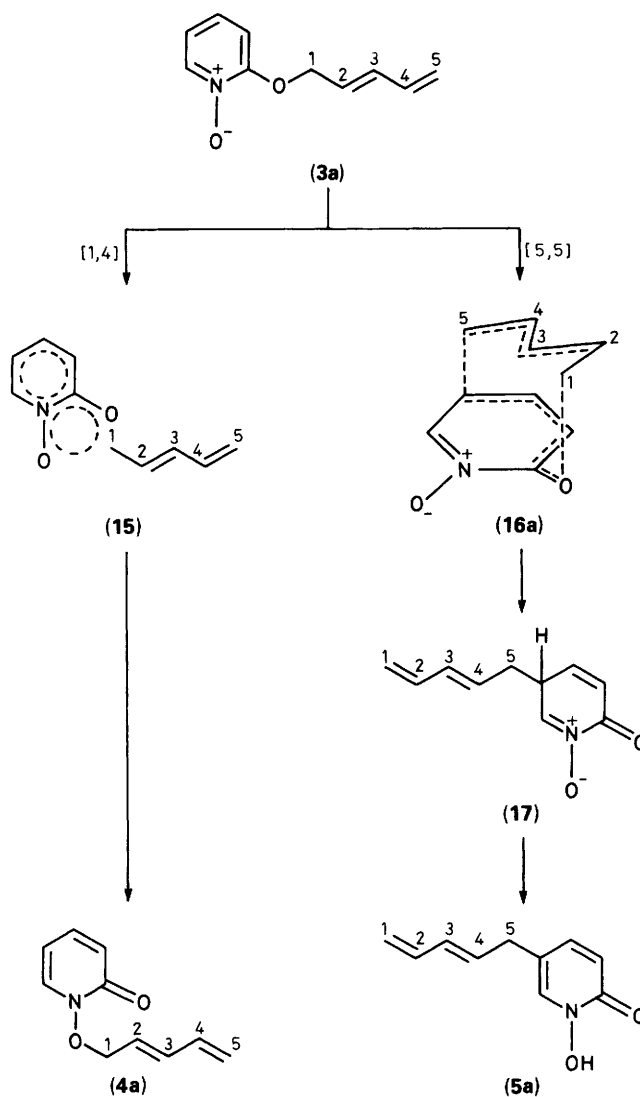
The important work by Frátar and Schmid¹² which led to the discovery of the [5,5] sigmatropic rearrangement of (2*E*)-penta-2,4-dienyl phenyl ethers rested upon the labelling of the pentadienyl group by methyl substituents. Thus, thermal rearrangement (diethylaniline; 186 °C) of the ether (**9b**) gave the [3,3] product (**10b**) (27% yield) and the [5,5] product (**10c**) (56% yield). Similarly, rearrangement of the ether (**9c**) gave the [3,3] product (**10c**) (58% yield) and the [5,5] product (**11c**) (3% yield). The product ratios are markedly dependent upon the position of the methyl substituent on the (2*E*)-penta-2,4-dienyl group. Clearly this perturbation could be removed using a pentadienyl substituent specifically labelled with deuterium. The availability to us of (2*E*)-1,1-dideuteriopenta-2,4-dien-1-ol encouraged us to re-investigate the regioselectivity of the [5,5] sigmatropic rearrangement of the pentadienyl phenyl ethers (**9a**) and (**12**).



In formulae (**9**), (**10**), and (**11**): **a**, $R^1 = R^2 = H$; **b**, $R^1 = H$, $R^2 = Me$; **c**, $R^1 = Me$, $R^2 = H$

The aryl ethers (**9a**) and (**12**) were synthesised by a method developed by Goering and Kimoto.¹⁵ (2*E*)-Penta-2,4-dien-1-ol and 2,4-dinitrofluorobenzene in triethylamine gave the corresponding 2,4-dinitrophenyl ether which by reaction with sodium phenoxide in diglyme gave (2*E*)-penta-2,4-dienyl

phenyl ether (**9a**). (2*E*)-1,1-Dideuteriopenta-2,4-dienyl phenyl ether (**12**) was similarly prepared. Thermal rearrangement (diethylaniline; 186 °C; 5 h) of the ether (**9a**) gave 2-(3-penta-1,4-dienyl)phenol (**10a**) (25% yield) and 4-[(2*E*)-penta-2,4-dienyl]phenol (**11a**) (40% yield). The dideuterio-derivative (**12**) similarly yielded the products (**13**) (23% yield) and (**14**) (38% yield). It was established by examination of the mass spectra and NMR spectra of the products that the rearrangement (**12**)→(**14**) proceeded regiospecifically with complete retention of deuterium. This result requires that (i) the product (**14**) is formed directly by a [5,5] sigmatropic rearrangement (**12**)→(**14**) and (ii) a sequence of two [3,3] sigmatropic rearrangements involving the dideuterio derivative (**13**) as an intermediate cannot be involved.



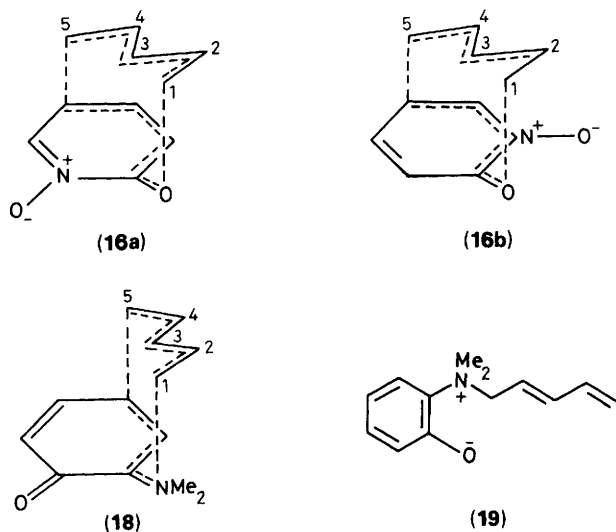
Scheme 2. Regiospecific [1,4] and [5,5] sigmatropic rearrangements of 2-pentadienyloxy pyridine *N*-oxide (**3a**)

The regiospecificity of the [1,4] and [5,5] sigmatropic rearrangements of 2-pentadienyloxy pyridine *N*-oxides (**3**) provides excellent support for the view summarised in Scheme 2 that the thermal transformation (**3**)→(**4**) + (**5**) involves concerted [1,4] and [5,5] sigmatropic rearrangements, respectively, associated with the transition states (**15**) and (**16a**) or (**16b**). Although transition state (**16a**) is included in Scheme 2, this does not

Table. Thermal rearrangement (100 °C; 90 min) of 2-[(*E*)-penta-2,4-dienyloxy]pyridine *N*-oxide (**3a**) in various solvents.

| Solvent | Product composition (%) | |
|---------------------|---|---|
| | [1,4] Rearrangement product (4a) | [5,5] Rearrangement product (5a) |
| Tetrachloroethylene | 95 | 5 |
| Toluene | 83 | 17 |
| Dioxane | 47 | 53 |
| Diethyl ketone | 44 | 56 |
| Aniline | 34 | 66 |
| Dimethyl sulphoxide | 32 | 68 |
| Dimethylformamide | 30 | 70 |
| Formamide | 3 | 97 |
| Water | 2 | 98 |

imply that we have any experimental basis for preferring transition state (**16a**) to transition state (**16b**). However, it must be emphasised that the *E*-stereochemistry of the pentadienyl residue in both the precursor (**3**) and in the product (**5**) is good evidence for the transition state (**16a**) or (**16b**) proposed for the [5,5] sigmatropic rearrangement (Scheme 2). This corresponds to the type-B stereochemistry proposed for the [5,4] sigmatropic rearrangements of allyl[(*E*)-penta-2,4-dienyl]ammonium ylides.⁸ In addition, it may be noted that there is an appealing correspondence between the transition state (**16**) and the transition state (**18**) proposed⁹ for the [5,4] sigmatropic rearrangement of *N*-pentadienyl-2-oxyanilinium ylides (**19**).



The influence of solvent polarity upon the periselectivity between [1,4] and [5,5] sigmatropic rearrangements of 2-[(*E*)-penta-2,4-dienyloxy]pyridine *N*-oxide (**3a**) has been investigated. The results (Table) show that the [1,4] sigmatropic rearrangement is favoured in solvents of low polarity, whereas the [5,5] sigmatropic rearrangement is favoured in solvents of high polarity. These observations are in accord with the views summarised in Scheme 2. The [1,4] sigmatropic rearrangement proceeds from a dipolar precursor (**3a**), via the transition state (**15**) which is accompanied by charge dissipation, to the product (**4a**). This sequence is associated with a reduction of charge separation and could therefore operate satisfactorily in a solvent of low polarity. In contrast, there is a maintenance of charge separation during the [5,5] sigmatropic rearrangement (**3a**)→(**17**)→(**5a**) until the last step (**17**)→(**5a**) occurs in which there is a prototropic change. It follows that the [5,5] sigmatropic

rearrangement would be encouraged by solvents of high polarity. Finally, it may be mentioned that the [1,4] sigmatropic rearrangement (**3c**)→(**4c**) occurs exclusively and quantitatively when the crystalline solid is stored (26 months) at −15 °C.

There is obviously a close mechanistic similarity between the [5,5] sigmatropic rearrangements of pentadienyl phenyl ethers and 2-pentadienyloxypyridine *N*-oxides. It is interesting that the latter rearrangement takes place under milder conditions. Furthermore, this investigation has revealed that there is a striking influence of structure upon the periselectivity between [3,3] and [5,5] sigmatropic rearrangements which could not have been expected on the basis of current theoretical treatments of pericyclic reactions. Pentadienyl phenyl ethers exhibit [3,3] and [5,5] sigmatropic rearrangements. In contrast, 2-pentadienyloxypyridine *N*-oxides do exhibit [5,5] but do not exhibit [3,3] sigmatropic rearrangements.

Experimental

The general methods are those recorded in reference 1.

(*E*)-Penta-2,4-dienyl-1-ol (**1a**).—(*E*)-Penta-2,4-dienoic acid¹⁶ (98.1 g), toluene-*p*-sulphonic acid (5.9 g), benzene (600 ml), and ethanol (295 ml) were heated under reflux (50 h) and water was removed azeotropically using a Dean-Stark separator. Addition of water, ether extraction, and fractional distillation yielded ethyl (*E*)-penta-2,4-dienoate (80.7 g, 64%) as a colourless liquid, b.p. 59–60 °C at 10 Torr (lit.¹⁷ 57–57.5 °C at 13 Torr); ν_{\max} (liquid film) 2 970, 1 715, 1 640, 1 600, 1 300, 1 260, 1 200, and 1 140 cm^{-1} ; δ ABCDE system, δ_A 5.58, δ_B 5.46, δ_C 6.44, δ_D 7.25, δ_E 5.90 [J_{AB} 1, J_{AC} 17, J_{BC} 10, J_{CD} 10, J_{DE} 15 Hz; $H_AH_BCH=CHCH=CHCO$], δ 4.19 (q, J 7 Hz, OCH_2CH_3), and δ 1.28 (t, J 7 Hz, OCH_2CH_3).

A solution of ethyl (*E*)-penta-2,4-dienoate (12.61 g) in ether (50 ml) was added dropwise to a stirred suspension of lithium aluminium hydride (3.79 g) in ether (200 ml) at −25 °C. The mixture was stirred at −10 °C for 3 h, then moist ether was cautiously added. The mixture was then acidified with 1M sulphuric acid and extracted with ether. After washing (10% aqueous sodium hydrogencarbonate) and drying (anhydrous potassium carbonate), evaporation at room temperature yielded a residue which was distilled at 0.05 Torr without external heating directly into a cold-trap receiver cooled in liquid nitrogen. This yielded (*E*)-penta-2,4-dien-1-ol as a colourless oil (6.64 g, 79%); ν_{\max} (liquid film) 3 300, 2 850, 1 603, 1 080, 955, and 895 cm^{-1} ; δ ABCDEX₂ system, δ_A 5.16, δ_B 5.06, δ_C 6.15–6.40, δ_D 6.15–6.40, δ_E 5.78, δ_X 4.10 [J_{AC} 16, J_{BC} 8, J_{DE} 15, J_{EX} 6 Hz; $CH_AH_BCH=CHCH=CHC(H_X)_2O$], and δ 3.61 (s, OH).

(*E*)-1,1-Dideuteriopenta-2,4-dien-1-ol [cf. (**1a**)].—Reduction of ethyl (*E*)-penta-2,4-dienoate (12.61 g) with lithium aluminium deuteride (4.19 g) as in the preceding experiment gave (*E*)-1,1-dideuteriopenta-2,4-dien-1-ol (7.23 g, 86%) (Found: M^{+} , 86. $C_5H_6D_2O$ requires M , 86). Its NMR spectrum corresponded exactly with that of (*E*)-penta-2,4-dien-1-ol (**1a**) except for simplification due to the absence of H_EH_X coupling and the absence of the signal at δ_X 4.10. This established the incorporation of deuterium (> 98 atom %D) at C-1.

2-[(*E*)-Penta-2,4-dienyloxy]pyridine *N*-oxides (**3**).—The following procedure is typical. A solution of (*E*)-penta-2,4-dien-1-ol (1.26 g) in tetrahydrofuran (10 ml) was added to a stirred suspension of sodium hydride (380 mg) in tetrahydrofuran (25 ml). After 15 min, a solution of 2-chloropyridine *N*-oxide (**2a**) (1.55 g) in tetrahydrofuran (15 ml) was added. After 2 h, the mixture was filtered (Hyflo Supercel), evaporated, and the residue purified by short-path column chromatography (silica

gel; chloroform-methanol, 94:6). Crystallisation from ethyl acetate-pentane yielded 2-[(2E)-penta-2,4-dienyloxy]pyridine *N*-oxide (**3a**) (1.73 g, 72%) as colourless rhombs, m.p. 69–71 °C (Found: C, 67.5; H, 6.1; N, 7.9%; M^+ , 177. $C_{10}H_{11}NO_2$ requires C, 67.8; H, 6.2; N, 7.9%; M , 177); ν_{\max} 2 970, 1 608, 1 565, 1 500, 1 438, 1 311, 1 115, and 1 000 cm^{-1} ; δ 6.86–7.02 (m, 3-H), 7.22 (t, J 8 Hz, 4-H), 6.86–7.02 (m, 5-H), and 8.26 (dd, J 7 and 2 Hz, 6-H), ABCDEX₂ system, δ_A 5.26, δ_B 5.17, δ_C 6.23–6.47, δ_D 6.23–6.47, δ_E 5.92, δ_X 4.91 [J_{AC} 16, J_{BC} 14, J_{DE} 14, J_{EX} 7 Hz; OC(H_X)₂-CH_E=CH_DCH_C=CH_AH_B].

The pyridine *N*-oxides (**3b**) and (**3c**) were prepared by a similar procedure from (2E)-2-methylpenta-2,4-dien-1-ol (**1b**)⁸ and (2E)-4-methylpenta-2,4-dien-1-ol (**1c**).⁸ Their properties and characterisation are summarised below.

2-[(2E)-2-Methylpenta-2,4-dienyloxy]pyridine *N*-oxide (**3b**) (65% yield), colourless rhombs, m.p. 72–73 °C, from ethyl acetate-light petroleum (Found: C, 68.9; H, 7.0; N, 7.2%; M^+ , 191. $C_{11}H_{13}NO_2$ requires C, 69.1; H, 6.9; N, 7.3%; M , 191); ν_{\max} 2 970, 1 610, 1 565, 1 500, 1 435, 1 305, 1 270, 1 118, 985, and 912 cm^{-1} ; δ 6.88–6.98 (m, 3-H), 7.26 (t, J 7 Hz, 4-H), 6.88–6.98 (m, 5-H), 8.28 (d, J 7 Hz, 6-H), ABCDX₂ system, δ_A 5.26, δ_B 5.19, δ_C 6.57, δ_D 6.18, δ_X 4.82 [J_{AC} 18, J_{BC} 11, J_{CD} 11 Hz; OC(H_X)₂CMe=CH_DCH_C=CH_AH_B], and δ 1.88 (s, CH₃).

2-[(2E)-4-Methylpenta-2,4-dienyloxy]pyridine *N*-oxide (**3c**) (75% yield), colourless rhombs, m.p. 68–69 °C, from ethyl acetate-light petroleum (Found: C, 69.1; H, 7.1; N, 7.4%; M^+ , 191. $C_{11}H_{13}NO_2$ requires C, 69.1; H, 6.9; N, 7.3%; M , 191); ν_{\max} 2 970, 1 610, 1 500, 1 440, 1 310, 1 270, 1 118, and 965 cm^{-1} ; δ 6.97–6.88 (m, 3-H), 7.27 (dt, J 9 and 2 Hz, 4-H), 6.97–6.88 (m, 5-H), 8.28 (dd, J 7 and 1.5 Hz, 6-H), ABDEX₂ system, δ_A 5.00–5.10, δ_B 5.00–5.10, δ_D 6.46, δ_E 5.88, δ_X 4.94 [J_{DE} 16 Hz, J_{EX} 7 Hz; other coupling constants could not be determined by first order analysis due to overlap of signals; OC(H_X)₂CH_E=CH_DCMe=CH_AH_B], and δ 1.85 (s, CH₃).

2-[(2E)-1,1-Dideuteriopenta-2,4-dienyloxy]pyridine *N*-oxide (**6a**), colourless rhombs, m.p. 73–74 °C, from ethyl acetate-pentane (Found: M^+ , 179. $C_{10}H_9D_2NO_2$ requires M , 179). Its NMR spectrum corresponded exactly with that of 2-[(2E)-penta-2,4-dienyloxy]pyridine *N*-oxide (**3a**) except for simplification due to the absence of H_EH_X coupling and the absence of the signal at δ_X 4.91. This established the incorporation of deuterium (> 98 atom %D) at C-1 of the pentadienyloxy group.

Thermal Rearrangement of 2-[(2E)-Penta-2,4-dienyloxy]pyridine *N*-Oxides (3): Formation of N-[(2E)-Penta-2,4-dienyloxy]-2-pyridones (4) and N-Hydroxy-5-[(2E)-penta-2,4-dienyl]-2-pyridones (5).—The following procedure is typical. A solution of 2-[(2E)-penta-2,4-dienyloxy]pyridine *N*-oxide (**3a**) (140 mg) in dimethylformamide was heated (100 °C; 90 min) and then evaporated. The residue was dissolved in chloroform and extracted with 0.5M aqueous sodium hydroxide. The chloroform extract gave N-[(2E)-penta-2,4-dienyloxy]-2-pyridone (**4a**) (38 mg, 27%) as a colourless oil (Found: M^+ , 177.0776. $C_{10}H_{11}NO_2$ requires M , 177.0790); ν_{\max} 3 000, 1 665, 1 590, 1 535, 1 275, and 1 145 cm^{-1} ; δ 6.67 (d, J 9 Hz, 3-H), 7.31 (dd, J 9 and 7 Hz, 4-H), 6.10 (t, J 7 Hz, 5-H), 7.45 (d, J 7 Hz, 6-H), ABCDEX₂ system, δ_A 5.16–5.42, δ_B 5.16–5.42, δ_C 6.20–6.44, δ_D 6.20–6.44, δ_E 5.88, δ_X 4.82 [J_{DE} 15, J_{EX} 7 Hz; other coupling constants could not be determined by first order analysis due to overlap of signals; OC(H_X)₂CH_E=CH_DCH_C=CH_AH_B]. The alkaline extracts were acidified with 5M hydrochloric acid and extracted with chloroform to yield N-hydroxy-5-[(2E)-penta-2,4-dienyl]-2-pyridone (**5a**) (91 mg, 65%) as colourless oil (Found: M^+ , 177.0796. $C_{10}H_{11}NO_2$ requires M , 177.0790); ν_{\max} 2 925, 1 725, 1 665, 1 600, 1 525, 1 365, and 1 000 cm^{-1} ; δ 6.67 (d, J 9 Hz; 3-H), 7.24 (d, J 9 Hz, 4-H), 7.59 (s, 6-H), ABCDEX₂ system, δ_A 5.18, δ_B 5.07, δ_C 6.33, δ_D 6.10, δ_E 5.75,

δ_X 3.21 [J_{AC} 17, J_{BC} 10, J_{CD} 10, J_{DE} 15, J_{EX} 7 Hz; C(H_X)₂CH_E=CH_DCH_C=CH_AH_B].

The thermal rearrangements of the pyridine *N*-oxides (**3b**), (**3c**), and (**3d**) were similarly examined. The properties, characterisation, and relative yields of the corresponding products (**4**) and (**5**) are summarised below.

N-[(2E)-2-Methylpenta-2,4-dienyloxy]-2-pyridone (**4b**) (43% yield), a colourless oil (Found: M^+ , 191.0949. $C_{11}H_{13}NO_2$ requires M , 191.0946); ν_{\max} 2 990, 2 760, 1 665, 1 590, 1 535, 1 275, 1 142, 1 100, and 915 cm^{-1} ; δ 6.67 (d, J 9 Hz, 3-H), 7.32 (dt, J 7 and 1.5 Hz, 4-H), 6.00–6.20 (m, 5-H), 7.42 (dd, J 7 and 1.5 Hz, 6-H), ABCDX₂ system, δ_A 5.23, δ_B 5.19, δ_C 6.55, δ_D 6.67, δ_X 4.70 [J_{AC} 16, J_{BC} 10, J_{CD} 9 Hz; OC(H_X)₂CMe=CH_DCH_C=CH_AH_B], and 1.95 (s, CH₃).

N-Hydroxy-5-[(2E)-4-methylpenta-2,4-dienyl]-2-pyridone (**5b**) (55% yield), a colourless oil (Found: M^+ , 191.0944. $C_{11}H_{13}NO_2$ requires M , 191.0946); ν_{\max} 3 000, 1 660, 1 550, 1 495, 1 425, 1 328, 968, and 890 cm^{-1} ; δ 6.67 (d, J 9 Hz, 3-H), 7.26 (dd, J 9 and 2.5 Hz, 4-H), 7.59 (d, J 2.5 Hz, 6-H), ABDEX₂ system δ_A 4.94, δ_B 4.94, δ_D 6.18, δ_E 5.65, δ_X 3.23 [J_{DE} 16, J_{EX} 7 Hz; C(H_X)₂CH_E=CH_DCMe=CH_AH_B], and 1.82 (s, CH₃).

N-[(2E)-4-Methylpenta-2,4-dienyloxy]-2-pyridone (**4c**) (42% yield), a colourless oil (Found: M^+ , 191.0944. $C_{11}H_{13}NO_2$ requires M , 191.0946); ν_{\max} 3 000, 1 665, 1 590, 1 535, 1 455, 1 375, 1 275, 1 140, 1 100, 970, 940, 900, and 870 cm^{-1} ; δ 6.68 (d, J 9 Hz, 3-H), 7.28 (ddd, J 9, 7, and 2 Hz, 4-H), 6.08 (t, J 7 Hz, 5-H), 7.44 (dd, J 7 and 2 Hz, 6-H), ABDEX₂ system, δ_A 5.07, δ_B 5.02, δ_D 6.39, δ_E 5.84, δ_X 4.83 [J_{AB} 1, J_{DE} 15, J_{EX} 7 Hz; OC(H_X)₂CH_E=CH_DCMe=CH_AH_B], and 1.85 (s, CH₃). Compound (**4c**) was also produced (100% yield) when crystalline 2-[(2E)-4-methylpenta-2,4-dienyloxy]pyridine *N*-oxide (**3c**) was stored in the refrigerator (–15 °C; 26 months).

N-Hydroxy-5-[(2E)-2-methylpenta-2,4-dienyl]-2-pyridone (**5c**) (55% yield), a colourless oil (Found: M^+ , 191.0947. $C_{11}H_{13}NO_2$ requires M , 191.0946). ν_{\max} 3 000, 1 655, 1 550, 1 420, 1 358, 1 260, 1 142, 1 115, 985, and 905 cm^{-1} ; δ 6.66 (d, J 9 Hz, 3-H), 7.24 (dd, J 9 and 3 Hz, 4-H), 7.60 (d, J 3 Hz, 6-H), ABCDX₂ system, δ_A 5.17, δ_B 5.08, δ_C 6.55, δ_D 5.90, δ_X 3.13 [J_{AC} 17, J_{BC} 10, J_{CD} 10 Hz; C(H_X)₂CMe=CH_DCH_C=CH_AH_B], 1.70 (s, CH₃), and 9.1 (br s, OH).

4-Nitro-N-[(2E)-penta-2,4-dienyloxy]-2-pyridone (**4d**). This compound was formed by rearrangement at room temperature of the pyridine *N*-oxide (**3d**) produced by, but not isolated from, the reaction between 2-chloro-4-nitropyridine *N*-oxide (**2b**) and (2E)-penta-2,4-dien-1-ol (**1a**). The rearrangement product (**4d**) was obtained (29% yield) as yellow crystals, m.p. 79–80 °C, from ethyl acetate-pentane (Found: C, 53.9; H, 4.4; N, 12.3%; M^+ , 222. $C_{10}H_{10}N_2O_4$ requires C, 54.05; H, 4.5; N, 12.6%; M , 222); ν_{\max} 3 010, 1 675, 1 610, 1 530, 1 345, 1 105, 1 000, and 910 cm^{-1} ; δ 7.42 (d, J 3 Hz, 3-H), 6.74 (dd, J 8 and 3 Hz, 5-H), 7.58 (d, J 8 Hz, 6-H), ABCDEX₂ system, δ_A 5.05–5.50, δ_B 5.05–5.50, δ_C 6.16–6.45, δ_D 6.16–6.45, δ_E 5.69–5.99, δ_X 4.80 [J_{EX} 8 Hz; the other coupling constants could not be determined by first-order analysis due to overlap of the signals; OC(H_X)₂CH_E=CH_DCH_C=CH_AH_B].

Thermal Rearrangement of 2-[(2E)-1,1-Dideuteriopenta-2,4-dienyloxy]pyridine *N*-Oxide (6a): Formation of N-[(2E)-1,1-Dideuteriopenta-2,4-dienyloxy]-2-pyridone (7a) and N-Hydroxy-5-[(2E)-5,5-dideuteriopenta-2,4-dienyl]-2-pyridone (8a).—The experiment was carried out and the products isolated exactly as described for the thermal rearrangement of the undeuteriated compound (**3a**). The neutral fraction gave N-[(2E)-1,1-dideuteriopenta-2,4-dienyloxy]-2-pyridone (**7a**) (50% yield) as a colourless oil (Found: M^+ , 179. $C_{10}H_9D_2NO_2$ requires M , 179). Its NMR spectrum corresponded exactly with that of the undeuteriated compound (**4a**) except for simplification due to the absence of H_EH_X coupling and the absence of the signal at

δ_X 4.82. This established the incorporation of deuterium (>98 atom %D) at C-1 of the pentadienyloxy group.

The basic fraction after acidification and extraction gave *N*-hydroxy-5-[(2*E*)-5,5-dideuteriopenta-2,4-dienyl]-2-pyridone (**8a**) (44% yield) as a colourless oil (Found: M^+ , 179. $C_{10}H_9D_2NO_2$ requires M , 179). Its NMR spectrum corresponded exactly with that of the undeuteriated compound (**5a**) except for simplification due to the absence of H_C, H_A and H_C, H_B coupling and the absence of signals at δ_A 5.18 and δ_B 5.07. This established the incorporation of deuterium (>98 atom % D) at C-5 of the pentadienyl group.

Synthesis and Thermal Rearrangement of 4-Nitro-2-[(2*E*)-1,1-dideuteriopenta-2,4-dienyloxy]pyridine *N*-Oxide (6b**): Formation of 4-Nitro-*N*-[(2*E*)-1,1-dideuteriopenta-2,4-dienyloxy]-2-pyridone (**7b**).—**Following the usual procedure, the reaction between 2-chloro-4-nitropyridine *N*-oxide (**2b**) and (2*E*)-1,1-dideuteriopenta-2,4-dien-1-ol [cf. (**1a**)] yielded 4-nitro-*N*-[(2*E*)-1,1-dideuteriopenta-2,4-dienyloxy]-2-pyridone (**7b**). Its NMR spectrum corresponded exactly with that of the undeuteriated compound (**4d**) except for simplification due to the absence of H_E, H_X coupling and the absence of the signal δ_X 4.80. This established the incorporation of deuterium (>98 atom % D) at C-1 of the pentadienyloxy group.

Solvent Effects upon the Thermal Transformation of 2-[(2*E*)-Penta-2,4-dienyloxy]pyridine *N*-Oxide (3a**).—**Solutions of 2-[(2*E*)-penta-2,4-dienyloxy]pyridine *N*-oxide (15 mg) were heated (100 °C; 90 min) in selected solvents (10 ml). The relative proportions of the two thermal rearrangement products were determined from the integrated intensities of the signals δ_X 4.82 and δ_X 3.21. These signals correspond to $(H_X)_2$ of the pentadienyl group of *N*-[2*E*-penta-2,4-dienyloxy]-2-pyridone (**4a**) (δ_X 4.82) and *N*-hydroxy-5-[(2*E*)-penta-2,4-dienyl]-2-pyridone (**5a**) (δ_X 3.21). The product ratios are summarised in the Table. The possibility of thermal interconversion between the rearrangement products (**4a-c**) and (**5a-c**) was firmly excluded by showing that these compounds were unchanged after being heated (154 °C; 2 h) in dimethylformamide solution.

(2*E*)-Penta-2,4-dienyl Phenyl Ether (9a).—A mixture of (2*E*)-penta-2,4-dien-1-ol (1.68 g), 2,4-dinitrofluorobenzene (3.72 g), and triethylamine (2.02 g) was heated (100 °C; 10 min). After cooling, addition of ether (100 ml), followed by washing with hydrochloric acid (5%), aqueous sodium carbonate (5%), and water, and drying, evaporation yielded an oil. This oil was dissolved in diglyme (20 ml) and the solution was added to a stirred solution of sodium phenoxide prepared from phenol (2.82 g) and sodium hydride (0.72 g) in diglyme (20 ml). The mixture was heated (50–60 °C; 49 h) and then cooled, diluted with water, and extracted with pentane. This extract was washed with aqueous sodium hydroxide (10%), water, and saturated brine, and dried. Evaporation yielded a residue which was purified by MPLC (Spherisorb 11 μ column; light petroleum) to give (2*E*)-penta-2,4-dienyl phenyl ether as a colourless oil (1.34 g; 42%); v_{max} (liquid film) 3 020, 2 910, 1 600, 1 500, 1 370, 1 300, 1 240, 1 170, 1 000, and 900 cm^{-1} ; δ 6.80 (d, J 8 Hz, 2-H and 6-H), 6.83 (t, J 8 Hz, 4-H), 7.16 (t, J 8 Hz, 3-H and 5-H), ABCDEX₂ system, δ_A 5.14, δ_B 5.03, δ_C 6.17–6.38, δ_D 6.17–6.38, δ_E 5.78, δ_X 4.50 [J_{AC} 14, J_{BC} 10, J_{DE} 14, J_{EX} 7 Hz; $OC(H_X)_2-CH_E=CH_DCH_C=CH_AH_B$].

(2*E*)-1,1-Dideuteriopenta-2,4-dienyl Phenyl Ether (12**).—**1,1-Dideuterio-(2*E*)-penta-2,4-dien-1-ol gave as in the preceding experiment (2*E*)-1,1-dideuteriopenta-2,4-dienyl phenyl ether (39% yield) as a colourless oil (Found: M^+ , 162. $C_{11}H_{10}D_2O$ requires M , 162). Its NMR spectrum corresponded exactly with

that of the undeuteriated compound (**9a**) except for simplification due to the absence of H_E, H_X coupling and the absence of the signal at δ_X 4.50. This established the incorporation of deuterium (>98 atom % D) at C-1 of the pentadienyloxy grouping.

Thermal Rearrangement of (2*E*)-Penta-2,4-dienyl Phenyl Ether (9a): Formation of 2-(3-Penta-1,4-dienyl)phenol (10a**) and 4-[(2*E*)-Penta-2,4-dienyl]phenol (**11a**).—**A solution of the ether (**9a**) (269 mg) in *N,N*-diethylaniline (1.5 ml) was heated (186 °C; 5 h) in a sealed, evacuated, thick-walled, glass tube. After cooling, the product was dissolved in pentane, and the solution washed with 1M sulphuric acid and then extracted with aqueous sodium hydroxide (10%). The alkaline extract was acidified and extracted with pentane. Evaporation of the pentane gave a phenolic residue (184 mg) which was fractionated into two compounds by MPLC [Spherisorb 11 μ column; light petroleum (b.p. 60–80 °C–ethyl acetate, 95:5)]. 2-(3-Penta-1,4-dienyl)-phenol (67 mg, 25%) was obtained as a colourless oil; v_{max} 3 310, 2 930, 1 485, 1 455, 1 265, 1 000, and 920 cm^{-1} ; δ 7.04–7.22 (m, 3-H and 5-H), 6.90 (t, J 8 Hz, 4-H), 6.83 (d, J 8 Hz, 6-H), AA'BB'CC'X system, $\delta_A = \delta_{A'}$, 5.00–5.30, $\delta_B = \delta_{B'}$, 5.00–5.30, $\delta_C = \delta_{C'}$, 6.00, δ_X 4.20–4.35 [J_{AC} 18, J_{BC} 10, J_{CX} 7 Hz; $CH_X(CH_C=CH_AH_B)_2$]. 4-[(2*E*)-Penta-2,4-dienyl]phenol (108 mg, 40%) was obtained as a colourless oil; v_{max} 3 600, 3 320, 2 930, 1 515, 1 170, 1 005, and 905 cm^{-1} ; δ 6.75 (d, J 9 Hz, 2-H and 6-H), 7.04 (d, J 9 Hz, 3-H and 5-H), ABCDEX₂ system, δ_A 5.12, δ_B 4.98, δ_C 6.32, δ_D 6.08 δ_E 5.81, δ_X 3.33 [J_{AC} 17, J_{BC} 11, J_{CD} 11, J_{DE} 15, J_{EX} 7 Hz; $C(H_X)_2CH_E=CH_DCH_C=CH_AH_B$].

Thermal Rearrangement of (2*E*)-1,1-Dideuteriopenta-2,4-dienyl Phenyl Ether (12**): Formation of 2-(1,1-Dideuteriopenta-1,4-dien-3-yl)phenol (**13**) and 4-[(2*E*)-5,5-Dideuteriopenta-2,4-dienyl]phenol (**14**).—**(2*E*)-1,1-Dideuteriopenta-2,4-dienyl phenyl ether gave as in the preceding experiment two phenolic products. 2-(1,1-Dideuteriopenta-1,4-dienyl)phenol (23% yield) was obtained as a colourless oil (Found: M^+ , 162. $C_{11}H_{10}D_2O$ requires M , 162). Its NMR spectrum corresponded exactly with that of the undeuteriated compound (**10a**) except that the signals (δ 5.30–5.00) had an integrated intensity corresponding to only two H. This established the presence of 50 ± 2 atom % D on the two terminal olefinic methylene groups. 4-[(2*E*)-5,5-Dideuteriopenta-2,4-dienyl]phenol (38% yield) was obtained as a colourless oil (Found: M^+ , 162. $C_{11}H_{10}D_2O$ requires M , 162). Its NMR spectrum corresponded exactly with that of the undeuteriated compound except for simplification due to the absence of H_C, H_A and H_C, H_B coupling and the absence of signals δ_A 5.12 and δ_B 4.98. This established the incorporation of deuterium (>98 atom % D) at C-5 of the pentadienyl group.

References

- 1 D. Alker, W. D. Ollis, and H. Shahriari-Zavareh, *J. Chem. Soc., Perkin Trans. 1*, 1990, 1623.
- 2 D. Alker, W. D. Ollis, and H. Shahriari-Zavareh, *J. Chem. Soc.*, 1990, preceding paper.
- 3 F. J. Dinan and H. Tieckelmann, *J. Org. Chem.*, 1964, **29**, 1650; J. E. Litster and H. Tieckelmann, *J. Am. Chem. Soc.*, 1968, **90**, 4361.
- 4 L. Tenud, S. Farooq, J. Seibl, and A. Eschenmoser, *Helv. Chim. Acta*, 1970, **53**, 2059.
- 5 U. Schöllkopf and I. Hoppe, *Tetrahedron Lett.*, 1970, 4527; *Liebigs Ann. Chem.*, 1972, **765**, 153.
- 6 F. Gerhart and L. Wilde, *Tetrahedron Lett.*, 1974, 475.
- 7 W. J. le Noble and M. R. Daka, *J. Am. Chem. Soc.*, 1978, **100**, 5961.
- 8 T. Laird and W. D. Ollis, *J. Chem. Soc., Chem. Commun.*, 1973, 658; T. Laird, W. D. Ollis, and I. O. Sutherland, *J. Chem. Soc., Perkin Trans. 1*, 1980, 2033.
- 9 W. D. Ollis, R. Somanathan, and I. O. Sutherland, *J. Chem. Soc., Chem. Commun.*, 1973, 661; *J. Chem. Soc., Perkin Trans. 1*, 1981, 2930.

- 10 K. Chantrapromma, W. D. Ollis, and I. O. Sutherland, *J. Chem. Soc., Chem. Commun.*, 1977, 97; *J. Chem. Soc., Perkin Trans. 1*, 1983, 1041.
- 11 K. Chantrapromma, W. D. Ollis, and I. O. Sutherland, *J. Chem. Soc., Chem. Commun.*, 1978, 673.
- 12 G. Fráter and H. Schmid, *Helv. Chim. Acta*, 1968, **51**, 190; *ibid.*, 1970, **53**, 269.
- 13 A. Jefferson and F. Scheinmann, *Q. Rev.*, 1968, **22**, 391.
- 14 H.-J. Hansen and H. Schmid, *Chem. Br.*, 1969, **5**, 111; *Chima*, 1970, **24**, 89; *Tetrahedron*, 1974, **30**, 1959.
- 15 H. L. Goering and W. I. Kimoto, *J. Am. Chem. Soc.*, 1965, **87**, 1748.
- 16 E. Schjanberg, *Chem. Ber.*, 1937, **70**, 2385; H. O. House and G. H. Rasmusson, *J. Org. Chem.*, 1961, **26**, 4278; R. B. Woodward, F. E. Bader, H. Bickel, A. J. Frey, and R. W. Kierstead, *Tetrahedron*, 1958, **2**, 1.
- 17 J. D. R. Thomas and H. B. Watson, *J. Chem. Soc.*, 1956, 3958.

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