Functionalisation of Alkenes by a Cycloaddition–Cycloreversion Sequence. Part 1. Anionic Cycloreversion of Tetrahydrofuran and Tetrahydrothiophen Derivatives

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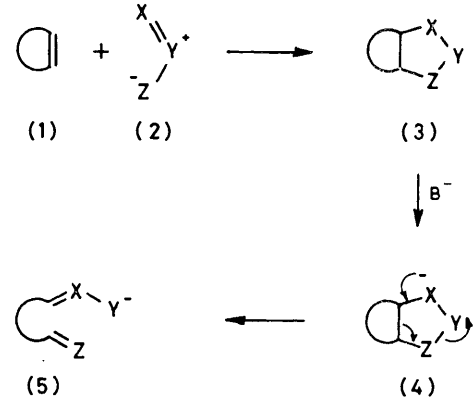
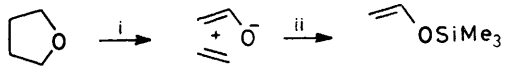
The cycloaddition of carbonyl and thiocarbonyl ylides to cycloalkenes gives adducts whose derivatives can be made to undergo anionic cycloreversion. In this way a new synthesis of an acyclic bifunctional alkane (16) from an unactivated cycloalkene (8) has formally been achieved by way of the intermediate (14). The cycloaddition of the thiocarbonyl ylide (24) to a variety of cycloalkenes occurs in good yield. The anionic cycloreversion of the sulphonium salt (21) to give the methylthiodiene (22) serves as a model for the cycloreversion of the salt (34), but this undergoes preferential elimination in base to give products (35) and (36).

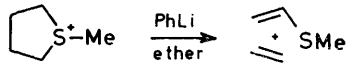
The cleavage of an alkene and subsequent functionalisation of the carbon atoms has traditionally been achieved by ozonolysis and elaboration of the product by aldol or Wittig reactions. About ten years ago Eschenmoser introduced the term ' indirect carboxolytic cleavage ' to describe a reaction in which the carbon atoms of an unactivated double bond were first functionalised by a cycloaddition reaction, and then cleaved with concomitant elaboration in a subsequent cycloreversion process.[1] We wished to extend this concept by the transformations summarised in Scheme 1, in which an alkene would first be converted into the dipolar cycloadduct (3); this after deprotonation to (4), should undergo anionic cycloreversion to give the diene (5). One example of such a combination of reagents has been reported by Kalvoda and Kaufmann [2] who studied the addition of a nitrile oxide to stilbene to give a dihydroisoxazole which upon anionic cycloreversion gave benzaldehyde and a substituted acetonitrile. Useful reviews of the fields of 1,3-anionic cycloadditions of organolithium compounds,[3] 1,3-dipole metathesis reactions,[4] 1,3-dipolar cycloreversions,[5] and [2 + 2]-cycloreversions [6] have appeared. These provide insight into the feasibility of the steps in Scheme 1. Thus the anionic cycloreversion of tetrahydrofuran to ethylene and acetaldehyde enolate (Scheme 2) is a well-studied reaction,[7] and there are scattered reports in the literature concerning the anionic cycloreversion of the ylides derived from *S*-substituted thiolanium salts (Scheme 3).[8] The tetrahydrofurans and tetrahydrothiophens (3; X = Z = CH_2, Y = O or S) are therefore attractive intermediates because they can be expected to be available by 1,3-dipolar cycloaddition of carbonyl (2; X = Z = CH_2, Y = O) and thiocarbonyl (2; X = Z = CH_2, Y = S) ylide to dipolarophiles.[9]



Scheme 1.



Scheme 2. *Reagents:* i, BuLi, hexane; ii, Me_3SiCl



Scheme 3.

In the oxygen series, tetracyanoethylene oxide (6) [10] exists above 100 °C in equilibrium with a small amount of its ring-opened isomer, the highly reactive carbonyl ylide (7), which reacts well with unactivated alkenes such as cyclohexene (8) to give the adduct (9).[11] Conversion of the tetranitrile (9) into the tetramethyl ester (10) according to the literature method,[11] followed by double demethoxycarbonylation with potassium chloride in wet dimethyl sulphoxide,[12] gave the diester (11). All attempts at anionic cycloreversion (*e.g.* NaH, $LiNPr^i_2$) of the diester (11) and of the model diester (12) and monoester (13) were completely unsuccessful. In each case starting material was recovered which suggested that the enolate anions, if they were being formed, were too stable to undergo cycloreversion.

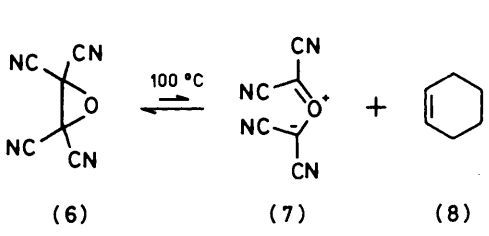
Another probable source of a carbonyl ylide is the reaction of bis(chloromethyl) ether with methyl-lithium–lithium iodide. This reagent is reported to give the *cis*-octahydroisobenzofuran (14) in the presence of cyclohexene (8) (Scheme 4).[12] Alternatively, the ether (14) can be prepared from the adduct of butadiene and maleic anhydride.[13] The reduced furan (14) was found to undergo cycloreversion with a variety of bases (Table) to give the enolate anion (15) which was trapped as the trimethylsilyl enol ether (16). The structure of (16) was confirmed by its conversion into the known 2,4-dinitrophenylhydrazone (18), m.p. 95 °C, previously obtained by Daniel and Weygand [14] in studies on the cycloreversion of the ammonium salt (17). The *E*-stereochemistry of the enol ether is assigned on the basis of the characteristic vicinal coupling constant (11.8 Hz)† observed for the enol ether proton at δ 6.1 in the ^1H n.m.r. spectrum.

† Typical vicinal coupling constants for the olefinic protons in *Z*- and *E*-enol ethers are 6.2—6.7 and 12.0—12.6 Hz, respectively (Jackman and Sternhell in ' Applications of NMR Spectroscopy in Organic Chemistry,' Pergamon, 1969, p. 302).

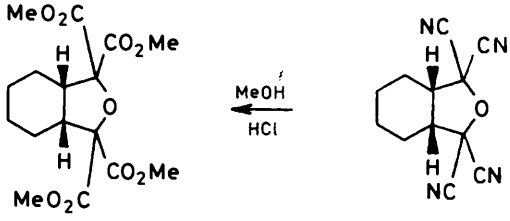
Table.

Entry	Base	Molar ratio of base: (14)	Solvent	Reaction conditions	Reaction time (h)	Yield (%) (14)	Yield (%) (16)
1	Bu^nLi	1	Hexane	Reflux	17	68	32
2	Bu^nLi	1	Hexane	Room temp.	15	100	0
3	Bu^nLi	1	Ether	Room temp.	22	100	0
4	Bu^nLi–TMEDA	1	Hexane–pentane	Reflux	16	79	21
5	Bu^sLi	1	Cyclohexane	0—5 °C	16	67	33
6	Bu^sLi	1	Cyclohexane	Room temp.	17	60	40 [a]
7	Bu^sLi–TMEDA	0.9	Cyclohexane	Room temp.	17	84	16
8	Bu^tLi	1	Pentane	−10 °C	17	100	0
9	Bu^tLi	1	Pentane	Room temp.	17	65	35
10	Bu^tLi	1	Pentane	Reflux	3	100	0
11	Bu^tLi	0.33	Pentane	Room temp.	20	62	38 [b]
12	Bu^tLi	1.5	Pentane	Room temp.	18	83	17
13	Bu^tLi	3	Pentane	Room temp.	19	Very low [c]	
14	Bu^tLi	3	Pentane	Reflux	22	78	22 [c]
15	PhLi	1	Ether	Room temp.	40	100	0

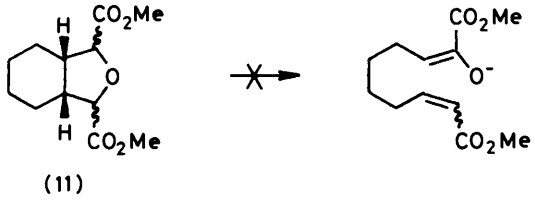
[a] Isolated yield 14%. [b] Adjusted to allow for excess of (14) in reaction. [c] Other g.c. peaks also visible.



(6) (7) (8)

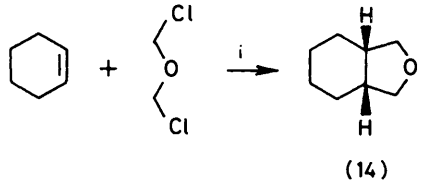


(10) (9)



(11)

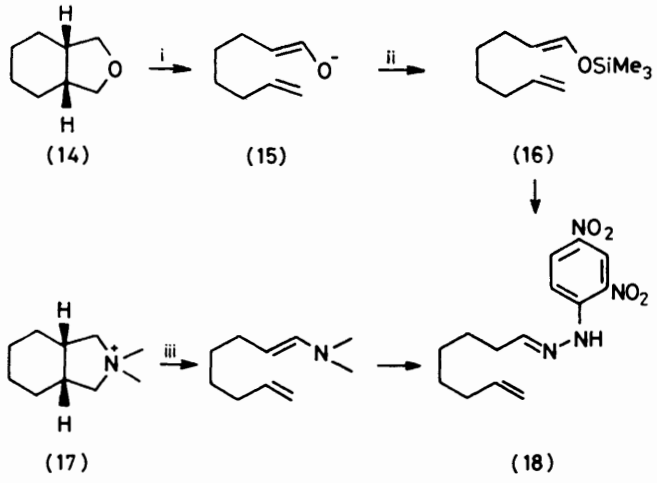
(12) (13)



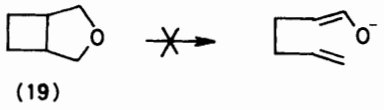
(14)

Scheme 4. *Reagents:* MeLi–LiI, C_6H_{12}, room temp., 12 h

The results presented in the Table were obtained by performing a calibrated gas chromatographic analysis of the reaction mixture, using pure samples of compounds (14) and (16) as reference standards. Owing to the similarity in boiling points of the starting material (14) and the enol ether (16), the best isolated yield of (16) was 14% although the g.c. analysis indicated an optimum yield of 40% using Bu^sLi as base in cyclohexane. As shown in the Table, under all reaction conditions investigated, even when a considerable excess of base was employed (entries 12—14), significant amounts of starting material (14) were recovered. This observation is in stark contrast to the results reported for the cycloreversion of tetrahydrofuran (THF),[7f] where respectable yields of the trimethylsilyl enol ether of acetaldehyde were obtained using Bu^nLi as base. In the present work this reagent was only effective under vigorous conditions (entries 1—3) and the reactivity was not significantly enhanced by complexation with tetramethylethylenediamine (TMEDA) (entry 4). Bu^sLi (entry 6) was the best base, but no improvement with added TMEDA was observed. An increase in the bulkiness of the base did not improve the yields (entries 8—15), nor was the result significantly altered by using either a deficiency (entry 11) or an excess (entries 12—14) of base. The only obvious difference between the reaction of tetrahydrofuran and that of the octahydroisobenzofuran (14) is that the ethylene is released to the reaction medium in the former whereas the alkene remains attached to the enolate product (15) in the latter. It is difficult to see how this difference can exert such a serious effect on the reaction path. Various speculations concerning the complexation of the base with the substrate and the reversibility of the cycloreversion can be made, but no firm information is available to resolve this question.



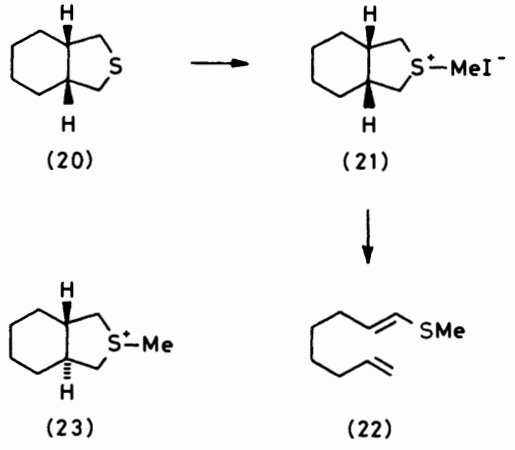
Reagents: i, Bu^{s}Li, C_6H_{12}, room temp., 17 h; ii, Me_3SiCl; iii, PhLi



It was anticipated that the anionic cycloreversion of the tetrahydrocyclobutafuran (19) should be much more favourable than that of (14) owing to the greater inherent strain present in (19). The preparation of this compound was carried out according to the general indications in the literature,[15] although it was difficult to obtain a pure sample. Treatment of compound (19) with Bu^{s}Li in cyclohexane at room temperature, followed by silylation of the reaction mixture, gave no product enol ether, and only starting material (19) was recovered. If the cycloreversion process is a concerted reaction, then the lack of reactivity of the hexahydrocyclobutafuran (19) may simply be due to the inability of the cyclobutane ring to flex sufficiently to allow the orbitals to overlap. Such a constraint may also apply partially to the octahydroisobenzofuran (14) but not at all to tetrahydrofuran.

In contrast to the oxygen series, much more success was achieved with the sulphur compounds. Methylation of the octahydroisobenzothiophen (20) with methyl iodide gave the sulphonium salt (21) which underwent smooth anionic cycloreversion (74%) in the presence of $LiNPr^i_2$ in tetrahydrofuran at room temperature. Phenyl-lithium[8a] was a less effective base (44% yield). The thioenol ether (22) possessed *E*-stereochemistry (*J* 15 Hz) and the carbon skeleton was confirmed by conversion into the derivative (18). Various studies have been reported on the relative acidities of the protons in *trans*-2-thiahydrindan sulphonium salt (23),[16] but no cycloreversions of this compound have been reported. The studies on compound (23) indicate that the most acidic proton is that which is most nearly perpendicular to the axis of the sulphur lone pair,[16b] although this depends also on the stereochemical integrity and the degree of hybridisation of the carbanionic centre in the ylide arising from deprotonation of (23).[17] The information on the stereochemistry of the sulphonium salt (21) and its possible stereoselective deprotonation is at present not available, and the question of the stereocontrol in the anionic cycloreversions of both (14) and (21) must await further investigation.

The very satisfactory cycloreversion results obtained for the sulphonium salt (21) gave us the opportunity to investigate the cycloaddition of thiocarbonyl ylides to alkenes. In contrast to the carbonyl ylide (7) and the reagent generated in Scheme 4, thiocarbonyl ylides usually add only to electron-deficient alkenes.[9] The best characterised thiocarbonyl ylide for the present investigation is the diethyl compound (24).[18] This was prepared and trapped with the dipolarophiles (25), (26), (27), and (28) to give the respective adducts (29), (30), (31), and (32) (Scheme 5). The adduct (31) was selected for an investigation of the cycloreversion reaction. In order to avoid possible deprotonation reactions, the carbonyl group was protected as the acetal (33) and the sulphonium salt (34) was formed with methyl Meerwein salt. Treatment of (34) with $LiNPr^i_2$ in THF did not give the required cycloreversion product but instead the elimination products (35a,b) and (36a,b) (two pairs of stereoisomers) which probably arose by α′,β-elimination as depicted by the intermediate (37).[19] Thus the sequence shown in Scheme 1 (3; Y = S) has to compete with this alternative mode of decomposition.

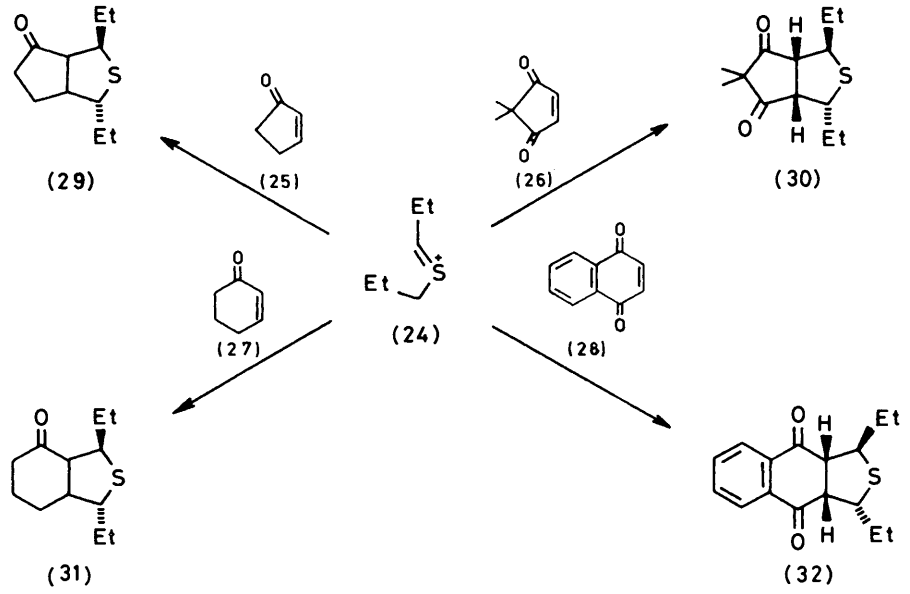


Conclusion

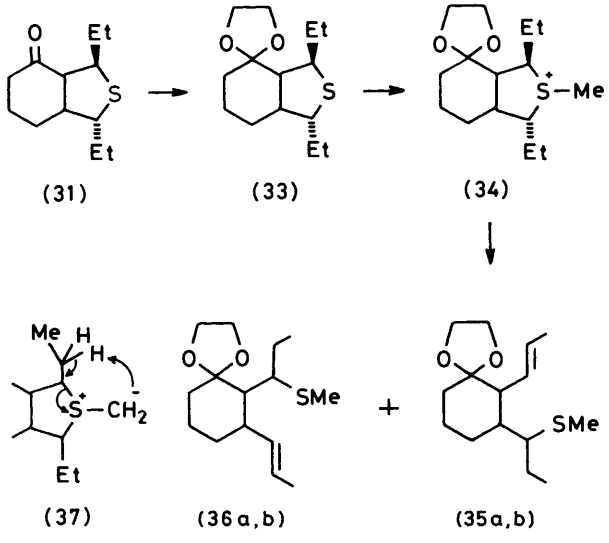
By a combination of the reaction shown in Scheme 4 and the cycloreversion of (14) to (16) the functionalisation of an unactivated alkene (cyclohexene) to give a bifunctional alkane as proposed in Scheme 1 has formally been achieved. The corresponding process in the sulphur series has been shown to have good synthetic potential provided the competing α′,β-elimination can be removed. This should be possible by using sulphonium salts in which the substituent on sulphur has no acidic protons, or preferably by removing the flanking substituents in the thiocarbonyl ylide. We and others[18] have devoted considerable effort to the preparation of the ylide $CH_2{=}S^+{-}CH_2{}^-$, but this work has so far been unsuccessful.

Experimental

M.p.s were determined with either a Köfler hot-stage or a Büchi 510 apparatus. ^{1}H n.m.r. spectra were recorded at 100 MHz with a Varian HA-100, at 90 MHz with a Varian EM-390, or at 60 MHz with a Varian EM-360 spectrometer, with tetramethylsilane as internal reference. ^{13}C N.m.r. spectra were recorded at 20 MHz on a Varian CFT-20 spectrometer. I.r. spectra were recorded as 2.5% (w/v) solutions with either a Perkin-Elmer 257 or a 297 spectrometer. Mass spectra were recorded with either an A.E.I. MS30 or an MS 902 instrument. Microanalyses were carried out by Mr. D. Flory and his Staff at the University Chemical Laboratory. Preparative layer chromatography was carried out on 20 × 20-cm glass plates coated to a thickness of 1 mm with Merck Kieselgel PF_{254}. The silica gel for column chromatography was Merck Kieselgel 60 (70—230 mesh) and Kieselgel 60 (230—400 mesh) for flash column chromatography.[20] Gas chromato-



Scheme 5.



graphic analyses were performed using a Perkin-Elmer F11 with f.i.d. on a 2-m column of 15% LAC (diethylene glycol adipate cross-linked with pentaerythritol) on Chromosorb AW *operating* at 130—160 °C.

cis-*Dimethyl Octahydroisobenzofuran*-1,3-*dicarboxylate* (11).—The tetranitrile (9) was converted into the tetraester (10) according to the method described by Linn and Benson.[11] A mixture of the tetraester (10) (2.397 g, 6.694 mmol), sodium chloride (322 mg, 5.509 mmol) and dimethyl sulphoxide (5 ml) containing water (0.24 ml) [12] was heated at 128—135 °C under a nitrogen stream for 13 h until CO_2 evolution had ceased. After cooling, the mixture was poured into water (150 ml) and this was extracted with ether (3 × 100 ml). The combined organic layers were washed with brine (100 ml), dried (Na_2SO_4), and evaporated to give a brown oil (1.399 g). This was distilled in a kugelrohr apparatus (b.p. 110—130 °C/0.35—0.7 mmHg) and the resulting yellow oil was flash chromatographed. After elution with ethyl acetate–light petroleum (b.p. 40—60 °C) (45 : 55) the *product* (11) was obtained as a colourless oil (795 mg, 49%): δ(CCl_4) 0.9—2.1 (8 H, m), 2.47 (2 H, m), 3.67 (6 H, overlapping s), 4.17, 4.33, 4.42, and 4.57 (2 H, all d's, *J* 4.5 Hz); $\nu_{max.}$ (CCl_4) 1 760 s, and 1 740s cm^{-1}; *m/e* 242 (M^+, 12%), 241 (52), and 123 (100) (Found: C, 59.2; H, 7.5. $C_{12}H_{18}O_5$ requires C, 59.5; H, 7.5%).

cis-*Octahydroisobenzofuran* (14).—A modification of the reported acid-catalysed cyclisation [13] of *cis*-1,2-bis(hydroxymethyl)cyclohexane [21] was used. The diol (19.3 g, 134 mmol) and commercial polyphosphoric acid (B.D.H.; 15 g) were stirred for 2 h over a steam-bath. The reaction mixture was diluted with water (100 ml) and extracted with dichloromethane (2 × 100 ml). The combined organic extracts were washed with water (100 ml), dried (Na_2SO_4), and evaporated. Residual water was removed by azeotropic distillation with benzene at atmospheric pressure and then the product was distilled to give the furan (14) [12,13] as a fragrant colourless oil (11.8 g, 70%), b.p. 67—67.5 °C/17 mmHg: δ (^1H) ($CDCl_3$) 1.50 (8 H, m), 2.20 (2 H, m), and 3.68 (4 H, m); δ(^{13}C) ($CDCl_3$) 26.7, 29.1, 41.9, and 75.7 p.p.m.

1-*Trimethylsilyloxyocta*-1,7-*diene* (16).—To the furan (14) (9.785 g, 77.7 mmol), cooled under argon in an ice-bath, was added s-butyl-lithium (1.2 M; 64.7 ml, 77.7 mmol) in cyclohexane in 10-ml batches during 15 min. The mixture was warmed to room temperature and stirred for 17 h during which time it first became yellow and then orange. After the mixture had been cooled in an ice-bath trimethylchlorosilane (19.7 ml, 155.4 mmol) was added slowly in 5-ml portions with stirring. The reaction mixture became pink and was allowed to warm to room temperature during 55 min. After being cooled in ice the reaction mixture was diluted with ice-cold water (200 ml) and extracted with ice-cold pentane (3 × 100 ml). The combined organic layers were dried (Na_2SO_4, $NaHCO_3$) and evaporated to give a residue which was fractionally distilled several times, each fraction being analysed by g.c. This gave a mixture (6.58 g) containing 43% of product and a fraction (2.18 g, 14%) containing the pure *silyl ether* (16), b.p. 95—100 °C/15 mmHg: δ($CDCl_3$) 0.14 (9 H, s), 1.35 (4 H, m), 1.94 (4 H, m), 4.74—5.04 (3 H, m), 5.74 (1 H, m), and 6.10 (1 H, dt, *J* 11.8 and 1.3 Hz); $\nu_{max.}$ (CCl_4) 3 035s, 1 640s, 992m, and 920m cm^{-1}; *m/e* 197 (M^+ − 1, 1%), 129

(25), 116 (10), 75 (38), and 73 (100) (Found: C, 66.5; H, 11.2. $C_{11}H_{22}OSi$ requires C, 66.6; H, 11.2%).

cis-*Hexahydrocyclobuta*[c]*furan* (19).—A mixture of *cis*-1,2-bis(hydroxymethyl)cyclobutane [15a] (1.71 g, 14.7 mmol) and polyphosphoric acid (1.59 g) was stirred at 100 °C (1 h). The brown reaction mixture was cooled, diluted with water (10 ml), and extracted with dichloromethane (2 × 10 ml). The combined organic extracts were washed with water (10 ml), dried (Na_2SO_4), and fractionally distilled at 760 mmHg. After most of the dichloromethane had been removed below 50 °C the product (19) (0.88 g) was obtained, b.p. 100—120 °C; δ($CDCl_3$) 1.5—2.4 (4 H, m), 2.9 (2 H, m), and 3.28 (m), 3.45 (m), 3.68 (s), 3.82 (s) (4 H in total). The product was contaminated with dichloromethane (δ 5.3) but further distillation resulted in decomposition. The ether (19) (76 mg, 0.78 mmol) was treated with Bu^sLi (0.65 ml, 0.78 mmol) at room temperature in cyclohexane for 23 h, and then worked up as described for the preparation of (16), but only the starting material (19) was obtained.

cis-2-*Methyl*-1,3,3a,4,5,6,7,7a-*octahydrobenzo*[c]*thiolium Iodide* (21).—A mixture of *cis*-octahydrobenzo[*c*]thiophen [21] (8.82 g, 62 mmol) and methyl iodide (7.65 g, 124 mmol) in absolute ethanol (20 ml) was stirred under nitrogen in the dark at room temperature for 5 days. The mixture was cooled to −10 °C and the resulting white precipitate was collected and recrystallised from ethanol (30 ml) to give the *sulphonium salt* (21) (12.77 g, 73%) as a white solid, m.p. 107—109 °C (decomp.); δ($CDCl_3$) 1.58 (8 H, m), 3.0 (2 H, m), 3.48 (3 H, s), and 3.7—3.9 (4 H, m) (Found: C, 38.1; H, 6.0; I, 44.9; S, 11.6. $C_9H_{17}SI$ requires C, 38.0; H, 6.0; I, 44.65; S, 11.3%).

(E)-1-*Methylthio-octa*-1,7-*diene* (22).—Lithium di-isopropylamide (1 mmol) in THF (2 ml) was added under dry argon to a stirred dispersion of the sulphonium salt (21) (143 mg, 0.5 mmol) in THF (2 ml). This mixture was stirred for 18.3 h at room temperature, poured into water (25 ml), and extracted with pentane (2 × 10 ml). The combined organic extracts were washed with water (2 × 10 ml), dried (Na_2SO_4), and evaporated to give a yellow oil (73 mg). Kugelrohr distillation of this material gave the *diene* (22) as a colourless oil (58 mg, 74%), b.p. 50—70 °C (bath temperature)/0.7 mmHg; δ($CDCl_3$) 1.3—1.7 (4 H, m), 1.9—2.4 (4 H, m), 2.25 (3 H, s), 4.82 (m), 5.02 (m), 5.10 (m) (2 H), and 5.98 (1 H, br d, *J* 15 Hz); $\nu_{max.}$ (CCl_4) 3 080m, 1 641m, 1 615, 992m, 936s, and 912s cm^{-1}; *m/e* 141 (M^+ − 15, 19%), 137 (38), 110 (58), 109 (27), 87 (49), and 78 (100) (Found: C, 69.1; H, 10.3. $C_9H_{16}S$ requires C, 69.2; H, 10.3%). Treatment of the sulphonium salt (21) with a two-fold excess of phenyl-lithium in ether at 0 °C for 20 h gave the diene (22) in 44% yield.

1,3-*Diethyl*-1,3,3a,5,6,6a-*hexahydrocyclopenta*[c]*thiophen*-4-*one* (29).—A solution containing a mixture of cyclopentenone (25) (3.64 g, 44.4 mmol) and *trans*-2,5-diethyl-1,3,4-Δ³-thiadiazoline (24) (3.19 g, 22.2 mmol) was boiled until nitrogen evolution had ceased (*ca.* 1 h). After evaporation of the solvent and fractional distillation the *adduct* (29) was obtained as an oil (2.89 g, 66%), b.p. 89—92 °C/1.25 mmHg; δ($CDCl_3$) 1.01 (6 H, t, *J* 7 Hz), 1.2—2.5 (8 H, m), 2.8—3.2 (3 H, m), and 3.56 (1 H, m); $\nu_{max.}$ (CCl_4) 1 740 cm^{-1}; *m/e* 198 (M^+, 31%), 169 (30), and 125 (100) (Found: C, 66.8; H, 9.1. $C_{11}H_{18}OS$ requires C, 66.6; H, 9.2%).

1,3-*Diethyl*-5,5-*dimethyl*-1,3,3a,6a-*tetrahydrocyclopenta*[c]*thiophen*-4,6(5H)-*dione* (30).—A solution of *trans*-2,5-ethyl-1,3,4-Δ³-thiadiazoline [18] (2.13 g, 14.8 mmol) and 2,2-dimethylcyclopent-4-ene-1,3-dione (26) [22] (3.69 g, 29.8 mmol) in benzene (40 ml) was heated under reflux for 1 h. The resulting dark brown solution was concentrated and fractionally distilled to give the *adduct* (30) (2.18 g, 61%) as a yellow oil, b.p. 92—95 °C/0.4 mmHg; δ($CDCl_3$) 1.05 (6 H, t, *J* 7 Hz), 1.13 (6 H, m), 1.2—2.3 (4 H, m), and 3.4—3.8 (4 H, m); $\nu_{max.}$ (CCl_4) 1 770s, and 1 730s cm^{-1}; *m/e* 240 (M^+, 39%), 166 (21), 116 (20), and 113 (100) (Found: C, 65.2; H, 8.3. $C_{13}H_{20}O_2S$ requires C, 65.0; H, 8.4%).

1,3-*Diethyl*-1,3,3a,6,7,7a-*hexahydrobenzo*[c]*thiophen*-4(5H)-*one* (31).—A solution of *trans*-2,5-diethyl-1,3,4-Δ³-thiadiazoline [18] (1.34 g, 9.3 mmol) and cyclohexenone (27) (1.79 g, 18.6 mmol) in benzene (20 ml) was boiled for 1 h. Evaporation of the solvent and fractional distillation of the residue gave first cyclohexenone and then the *adduct* (31) (0.61 g, 35%) as a yellow oil, b.p. 168 °C/18 mmHg; δ($CDCl_3$) 1.03 (6 H, t, *J* 7 Hz), 1.0—2.8 (12 H, m), and 2.9—3.9 (2 H, m); $\nu_{max.}$ (CCl_4) 1 720s cm^{-1}; *m/e* 212 (M^+, 38%), 183 (100), and 165 (35) (Found: C, 67.7; H, 9.6. $C_{12}H_{20}OS$ requires C, 67.9; H, 9.5%).

1,3-*Diethyl*-1,3,3a,9a-*tetrahydronaphtho*[2,3-c]*thiophen*-4,9-*dione* (32).—A solution of *trans*-2,5-diethyl-1,3,4-Δ³-thiadiazoline [18] (1.15 g, 8.08 mmol) and 1,4-naphthoquinone (28) (1.49 g, 9.43 mmol) in benzene (30 ml) was boiled for 1 h. Evaporation of the solvent gave a yellow oil which partly crystallised. This was triturated with ether, the crystals were filtered off, and the filtrate was chromatographed on Kieselgel (150 g). Elution of the column with 3—12% methyl acetate–hexane gave a fraction which was concentrated to dryness and recrystallised several times from pentane to give the *adduct* (32) (318 mg, 14.4%) as colourless crystals, m.p. 78—83 °C; δ($CDCl_3$) 0.5—2.0 (10 H, m), 3.1—4.6 (4 H, m), and 7.5—8.3 (4 H, m); $\nu_{max.}$ (KBr) 1 690s cm^{-1}; *m/e* 274 (M^+, 35%) 246 (20), 245 (100), and 160 (23) (Found: C, 69.8; H, 6.6. $C_{16}H_{18}O_2S$ requires C, 70.0; H, 6.6%).

1,3-*Diethyl*-1,3,3a,6,7,7a-*hexahydrobenzo*[c]*thiophen*-4(5H)-*one Ethylene Acetal* (33).—A mixture of the ketone (31) (1.09 g, 5.14 mmol), toluene-*p*-sulphonic acid monohydrate (100 mg), ethane-1,2-diol (0.62 g, 10 mmol), and dry benzene (270 ml) was boiled in a Dean–Stark apparatus for 19.75 h. The reaction mixture was washed with water (2 × 250 ml) and the combined aqueous layers were extracted with dichloromethane (50 ml). The dichloromethane and benzene extracts were combined, washed with water (2 × 50 ml), dried (Na_2SO_4), and evaporated. The residue was chromatographed on Kieselgel (165 g) and the column was eluted with ethyl acetate–hexane (10%, 500 ml followed by 15%, 500 ml). The latter fraction contained the required compound (1.19 g, 87%) which was distilled in a kugelrohr apparatus to give the *acetal* (33) as an oil, b.p. 115—120 °C (bath temperature)/0.35 mmHg; δ($CDCl_3$) 0.93 (6 H, t, *J* 7 Hz), 1.0—3.4 (14 H, m), and 3.92 (4 H, m); $\nu_{max.}$ (CCl_4) 2 965, 2 935, 2 875, 1 460, 1 380, 1 300, 1 270, 1 225, 1 190, 1 170, 1 155, 1 100, 1 080, 1 045, 1 000, 945, 910, and 865 cm^{-1}; *m/e* 256 (M^+, 100%), 227 (74), 195 (22), 168 (27), 165 (38), 155 (48), 141 (31), and 99 (75) (Found: C, 65.9; H, 9.4. $C_{14}H_{24}O_2S$ requires C, 65.6; H, 9.4%).

The Sulphonium Salt (34) *and its Cycloreversion.*—To a stirred solution of the ethylene acetal (33) (0.561 g, 2.19 mmol) in dry chloroform (10 ml) was added trimethyloxonium tetrafluoroborate [23] (393 mg, 2.65 mmol). The mixture was stirred at room temperature (17 h), then evaporated to give the crude 2-*methyl*-4-*oxo*-1,3,3a,4,5,6,7,7a-*octahydrobenzo*[c]*thiolium ethylene acetal salt* (34) as an oil; δ($CDCl_3$) 1.0—2.8 (16 H, m), 2.73 (s), 2.78 (s), 2.83 (s) (3 H), 3.3—4.2 (2 H, m), and 3.93 (4 H, m). This oil was dried by azeotropic removal of water using benzene. Anhydrous THF (10 ml) was added followed

by lithium di-isopropylamide (5.82 mmol) in THF (10 ml) at room temperature. After the brown reaction mixture had been stirred at room temperature (2.5 h) it was poured into water (400 ml) and extracted with dichloromethane (5 × 50 ml). The extracts were combined, dried (Na_2SO_4), and evaporated to give a brown oil (479 mg). This was purified by preparative layer chromatography on Kieselgel in 5% methyl acetate–hexane. Three compounds were obtained. The *thioether* (35a) (50 mg, 8.5%) distilled (kugelrohr) at b.p. 75—85 °C/0.6 mmHg; δ($CDCl_3$) 0.96 (3 H, t, *J* 7 Hz), 1.1—2.5 (10 H, m), 1.70 (3 H, d, *J* 5.5 Hz), 1.91 (3 H, s), 2.88 (1 H, dd, *J* 10, 3.5 Hz), 3.91 (4 H, s), and 5.2—6.8 (2 H, m). Irradiation at δ 2.98 caused half of the multiplet at δ 5.2—6.8 to simplify to a doublet (*J* 15 Hz) at δ 5.37. Irradiation at δ 1.82 caused the other half of the multiplet at δ 5.2—6.8 to collapse to a doublet (*J* 15 Hz) at δ 5.69 while the signal centred at δ 5.37 sharpened to a quintet (*J* 15, 10 Hz). Irradiation at δ 5.13 caused the multiplet at δ 2.88 to collapse to a broad singlet. Irradiation at δ 5.60 caused the doublet at δ 1.70 to collapse to a broad singlet. $\nu_{max.}$ (CCl_4) 2 965, 2 935, 1 450, 1 440, 1 380, 1 360, 1 290, 1 155, 1 100, 1 045, 970, 950, 925, and 865 cm^{-1}; *m/e* 270 (M^+, 18%), 223 (18), 181 (85), and 99 (100) (Found: C, 67.4; H, 9.4. $C_{15}H_{26}O_2S$ requires C, 66.6; H, 9.6%).

The *thioether* (36a) was a colourless oil (82 mg, 14%); δ($CDCl_3$) 0.99 (3 H, m), 1.0—2.7 (11 H, m) 1.68 (3 H, d, *J* 5 Hz), 2.03 (3 H, s), 3.87 (4 H, m), and 4.95—5.7 (2 H, m). Irradiation at δ 1.8 caused the multiplet at δ 4.95—5.7 to collapse to a doublet (*J* 15 Hz) at δ 5.48 and a quartet (*J* 15, 8 Hz) at δ 5.15. Irradiation at δ 2.32 caused half of the multiplet at 4.95—5.7 to collapse to a doublet (*J* 15 Hz) at δ 5.15. Irradiation at δ 5.48 caused the doublet at δ 1.68 to collapse to a singlet; $\nu_{max.}$ (CCl_4) 2 940, 2 880, 1 455, 1 450, 1 440, 1 380, 1 350, 1 290, 1 280, 1 270, 1 250, 1 210, 1 020, 975, 950, 930, 870, and 850 cm^{-1}; *m/e* 270 (M^+, 18%), 223 (16), 181 (100), and 99 (59) (Found: C, 67.2; H, 9.6. $C_{15}H_{26}O_2S$ requires C, 66.6; H, 9.7%).

The *thioether* (36b) (88 mg, 15%) was distilled (kugelrohr) at 100—110 °C (bath)/0.8 mmHg; δ ($CDCl_3$) 0.97 (3 H, t, *J* 7 Hz), 1.0—2.7 (14 H, m), 1.62 (3 H, d, *J* 5 Hz), 2.08 (3 H, s), 3.97 (4 H, m), and 5.0—5.7 (2 H, m). Irradiation at δ 1.75 collapsed half of the multiplet at δ 5.0—5.7 to a doublet (*J* 15 Hz) at δ 5.52. Irradiation at δ 2.73 collapsed the other half of the multiplet at δ 5.0—5.7 to a doublet (*J* 15 Hz) at δ 5.20. Irradiation at 5.05 caused the multiplet at δ 2.56 to collapse to a double doublet (*J* 15, 7 Hz). Irradiation at δ 5.44 caused the doublet at δ 1.62 to collapse to a singlet. $\nu_{max.}$ (CCl_4) 2 940, 2 885, 1 445, 1 380, 1 340, 1 300, 1 110, 1 050, 1 020, 970, and 950 cm^{-1}; *m/e* 270 (M^+, 23%), 223 (30), 181 (100), 137 (20), and 99 (70) (Found: C, 66.4; H, 9.8. $C_{15}H_{26}O_2S$ requires C, 66.6; H, 9.7%).

A fourth thioether (35b) (50 mg, 8.5%), thought to be an isomer of (35a), was isolated in an impure state; δ($CDCl_3$) 0.97 (3 H, t, *J* 7 Hz), 1.0—3.2 (13 H, m), 2.05 (3 H, s), 2.85 (1 H, m), 3.92 (4 H, m), and 5.1—6.2 (2 H, m).

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