Pergamon

Tetrahedron: Asymmetry Vol. 6, No. 12, pp. 2961-2970, 1995
Elsevier Science Ltd
Printed in Great Britain
0957-4166/95 $9.50+0.00

0957-4166(95)00393-2

Asymmetric Diels-Alder Reactions with a Chiral Spirodione, (6*S*,7*S*, 10*R*)-7-Isopropyl-10-methyl-1-oxaspiro[5.5]undec-3-ene-2,5-dione

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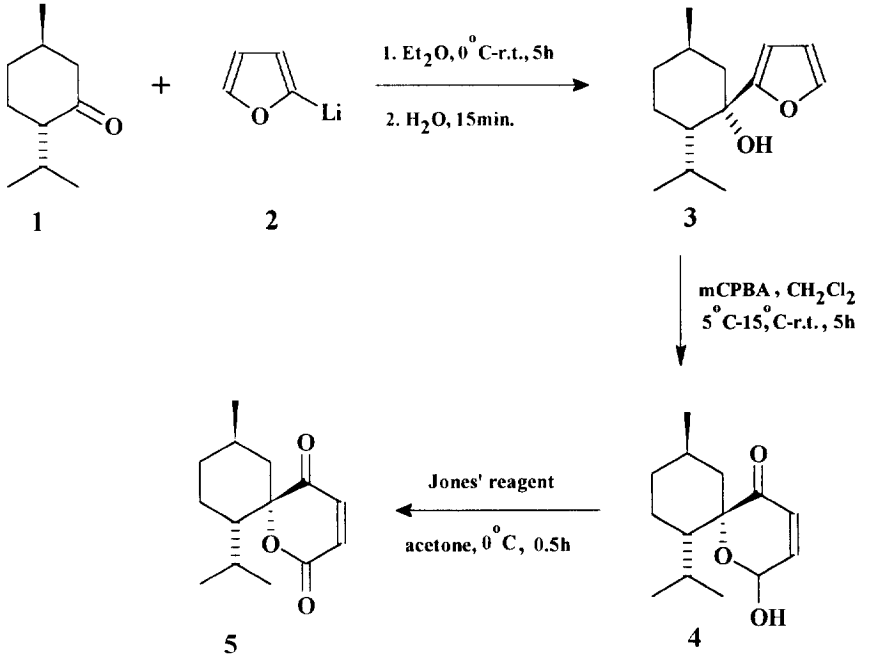
Abstract: The synthesis of the title spirodione, a new class of auxiliary based chiral synthon, using (-)-menthone having a unique carbon-carbon bond is described. Diels-Alder reactions were carried out with variety of dienes using the title auxiliary as a chiral dienophile in the presence of diethyl aluminium chloride as Lewis acid catalyst to afford the cycloadduct with good diastereoselectivity. The configurations of the chiral synthon and cycloadducts were determined by X-ray crystallography. Methodology for detachment of the chiral auxiliary from the cycloadducts has been developed.

Chiral auxiliary based asymmetric transformations are highly useful and versatile because of the reliable and often predictable absolute stereocontrol that is offered in many cases.[1] In recent years, there has been a tremendous upsurge of interest in asymmetric synthesis due to various emerging theories, e.g., Cieplak effect,[2] nucleophilic and electrophilic surface theory,[3] electrostatic interactions,[4] σ-π interactions,[5] FMO theory of stereoselection,[6] theory of steric consideration[7] and steric control of diastereoselection.[8]

Π-face stereoselection is at the heart of stereogenesis. A seminal report by Seebach et. al.[9] explains how the stereoelectronic effect plays a role in the asymmetric synthesis. The kinetic stereoelectronic effect rather than steric effects were shown to be responsible for efficient π-face stereoselectivity. In an earlier report by Seebach[10] the concept of 'chiral memory' and 'self reproduction of chirality' had been proposed. The enormous literature about asymmetric synthesis indicates that it is ever challenging. The challenge of control of absolute stereochemistry in Diels-Alder reactions[11] is evident from its prominent role in organic synthesis. More specifically, control of reactivity and modest to high asymmetric induction in Diels-Alder reaction were achieved using chiral catalysts,[12] chiral dienes,[13] or dienophiles.[11,14] However, only limited success has been achieved and synthetic utility has been severely restricted by the

necessity for Lewis acid catalysts, or the accessibility of the chiral auxiliary. Herein we report the synthesis of the title auxiliary derived from (-)-menthone having a unique carbon-carbon bond and its successful application to the preparation of enantiomerically pure Diels-Alder products.

The synthesis of chiral spirodione **5** was achieved according to the synthetic strategy depicted in Scheme 1. Thus (-)-menthone **1** was condensed with 2-furyllithium **2** in a stereospecific manner to give the *trans*-1-(2-furyl)-menthan-1-ol **3** in 95% yield. Compound **3** was subjected to oxidative cyclization by treatment with *m*-chloroperoxybenzoic acid, a stereospecific oxidation-rearrangement sequence[15] on the furan nucleus, ultimately leading to pyranone derivative **4**, which on subsequent treatment with Jones' reagent afforded the spirodione **5** as a single diastereomer in quantitative yield.



1 2 3 4 5

Scheme 1

The absolute configuration of **5** was determined unequivocally as (6*S*,7*S*,10*R*)-7-isopropyl-10-methyl-1-oxaspiro[5.5]undec-3-ene-2,5-dione based on single crystal X-ray analysis as shown in **Fig.1**. The isopropyl group of menthone was found *syn* to the C-O bond of the oxaspirosystem.Having established the absolute configuration of **5**, we realized that we had embarked on a novel skeleton for optical induction studies. In earlier studies by Seebach,[16] Demuth,[17] Ravindranathan,[18] Oppolzer,[19] Whitesell,[20] Enders[21] and Meyers[22] ester, thioketal, amides, hydrazones etc. were usually utilized for joining the auxiliary with the reaction site; whereas in our studies a carbon-carbon bond is utilized.

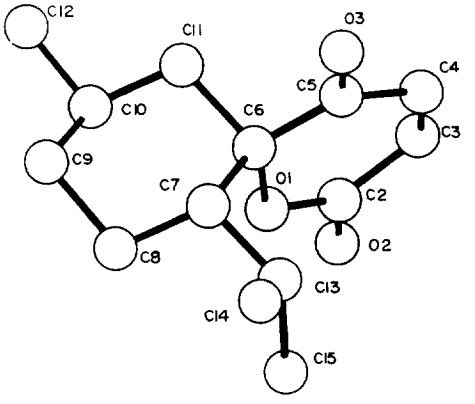
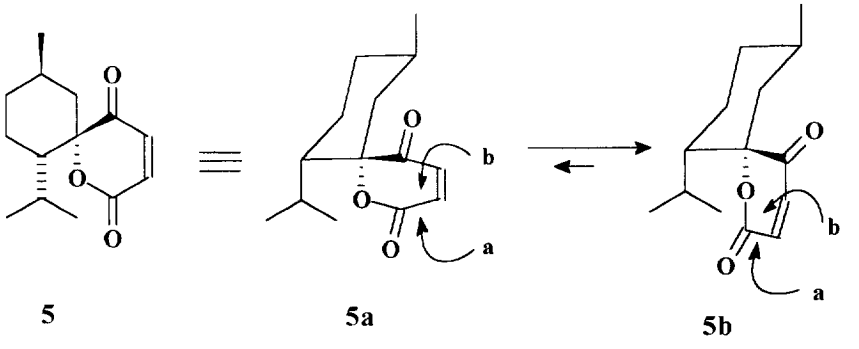


FIG.1: X-RAY STRUCTURE OF 5

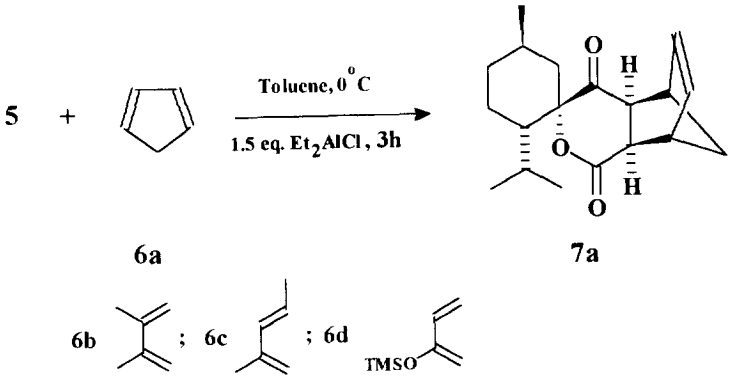
The chiral auxiliary **5** can exhibit two different facial selectivities as reported for the similar kind of skeleton.[16,17] Thus, reagents can approach from the 'a' side *cis* to the isopropyl group or from the 'b' side opposite to the isopropyl group, as shown in **Fig. 2**.



5 **5a** **5b**

Fig. 2

By taking advantage of the diastereotopic face differences in **5**, we have examined the Diels-Alder reaction, with a view of preparing optically active skeleta. The approach of the diene is based on the chiral auxiliary **5** which is expected to undergo π-face selective cycloaddition with a variety of dienes. Thus, the Diels-Alder reaction between chiral auxiliary **5** and diene such as cyclopentadiene **6a** and 2,3-dimethyl-1,3-butadiene **6b** in the presence of Lewis acid diethylaluminium chloride gave the cycloadducts **7a** and **7b** respectively as a single diastereomer in more than 95% yield (Table 1, entries 1 and 2), while reaction of other dienes e.g.,2-methyl-1,3-pentadiene **6c** and 2-(trimethylsilyloxy)-1,3-butadiene **6d** afforded the corresponding cycloadducts **7c** and **7d** respectively in 80-82% yield with 70-75% diastereoselectivity (Table 1, entries 3 and 4). The stereostructure of the cycloadduct **7a** was confirmed by the X-ray crystallographic analysis (**Fig. 3**).



Scheme 2

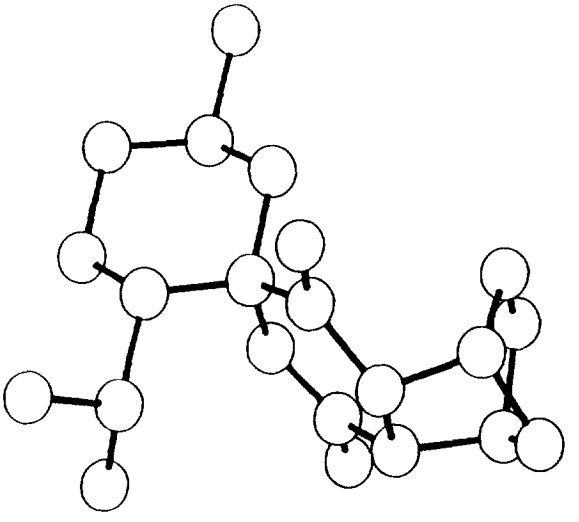


FIG 3 : X – RAY STRUCTURE OF 7a

Table 1: Asymmetric Diels-Alder Reactions of (6*S*,7*S*,10*R*)-7-isopropyl-10-methyl-1-oxaspiro[5.5]undec-3-ene-2,5-dione (**5**) in Toluene at 0°C.[a]

Entry	Diene	Yield[b](%)
1.	Cyclopentadiene	95
2.	2,3-Dimethyl-1,3-butadiene	95
3.	2-Methyl-1,3-pentadiene	80
4.	2-(Trimethlsilyloxy)-1,3-butadiene	82

a: No significant change in selectivity was observed when the temperature of the reaction was reduced further (-78°C).

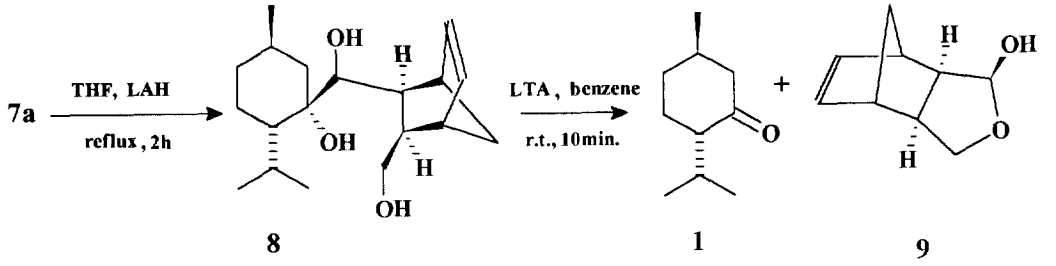
b: Yields of pure isolated products. Diastereoselectivity was determined on the basis of ^{13}C-NMR of the product.

Thus, remarkable stereofacial differentiation, 100% preference for 'b' side to 'a' side, as depicted in **Fig. 2** in the Diels-Alder reaction has been observed. In contrast to the literature report[17,23] the Diels-Alder reaction with new chiral auxiliary **5** proceeded in high stereoselectivity, but in completely reverse stereofacial selectivity. The reason for this unexpected reactivity pattern is not well understood. However, one reasonable explanation is to assume that the approach of the reagent, i.e.,diene from side 'a' should cause appreciable steric hindrance between the isopropyl and diene and hence the attack of the reagent occurs preferentially from 'b'side. Theoretical calculations are being carried out to determine the exact reason for this unusual observation.

Demuth et.al.[17] have reported the preferential formation of Diels-Alder adduct with similar kind of skeleton i.e.,dioxacyclohexenones in which attack of diene preferentially occurs from 'a' side. It was assumed that dioxacyclohexenone ring could adopt a sofa-conformation in solution just as in crystals an arrangement that exposes the 'a' side to the alkene. The stereoselectivities for thermal or photochemical addition to dioxinones were correlated with unidirectional pyramidalization of reacting centres. Similar observations were made by computational studies as well, which were experimentally verifiable.[9] It may be pertinent to mention here that complete reversal of selectivity (i.e.,preferential attack from 'b' side) has been reported in the literature for hydrogenation and methylation reactions with chiral auxiliary such as spirodioxinones.[17,23,24]

In the Diels-Alder reaction, the dienes **6c** and **6d** failed to give good stereoselection. One possible explanation of the above result is that chiral auxiliary **5** exists in an equilibrium between two conformers **5a** & **5b** (**Fig. 2**). The major diastereomer is formed *via* major conformer **5a** by 'b' side attack. It may be reasonable to assume that the minor diastereomer may be formed through the less stable conformer **5b** by the attack of diene from 'a' side. Thus, the change in stereoselectivity might be due to the change in the structural conformations of the spiroskeleton **5** in solution as discussed above.

Our next objective was the detachment of chiral auxiliary from the adduct to obtain the optically pure Diels-Alder product. A variety of methods employed for the detachment of chiral auxiliary such as Baeyer-Villiger oxidation followed by hydrolysis, photochemical degradation and basic hydrolysis followed by oxidation were unsuccessful. Equally, orthoester-dependent alcoholysis[25] also failed. However, when compound **7a** was treated with lithium aluminium hydride in refluxing THF, it gave triol **8** which on subsequent oxidative cleavage by lead tetraacetate afforded the optically pure menthone **1** and the lactol **9** as a single enantiomer.



8 1 9

Scheme 3

In conclusion, the synthesis of a new chiral auxiliary having a unique C-C bond has been achieved. The efficient application of this chiral auxiliary to a highly versatile Diels-Alder reaction has been demonstrated. Though, the rationalisation for the directorsin cycloaddition formation is still tentative, the experimental facts observed clearly show that the new chiral auxiliary is a versatile building block for a variety of chiral compounds. We continue to explore the synthetic application of this novel chiral auxiliary.

Experimental Section

General information

Melting points were determined with a Mel-Temp apparatus and are uncorrected. Infrared spectra were recorded on a Perkin-Elmer Model 683 grating infrared spectrophotometer. Proton and ^{13}C NMR spectra were recorded on various FT-80A, Bruker WH-90 FT NMR and Bruker AC-200 NMR spectrometers. The chemical shifts are reported in parts per million (δ) with tetramethylsilane as internal standard. Mass spectra were obtained with a Finnigan MAT-1020-B-70-eV mass spectrometer.

Preparation of trans-1-(2-furyl)-menthan-1-ol (3)

To a solution of freshly distilled furan **1** (4.21ml, 58mmol) in anhydrous ether (30ml), was added *n*-BuLi (29ml, 2.0M) dropwise under argon atmosphere at a temperature maintained between -10°C to -5°C. The reaction temperature was then allowed to come to room temperature and stirred for 1h. The temperature was then brought down to 0°C and (-)-menthone (8.9g, 58 mmol) was added in anhydrous ether (30ml) dropwise over a period of 30 minutes. The reaction temperature was gradually brought up to room temperature and stirred for 4 hrs. The contents of the flask were then poured into a beaker containing saturated ammonium chloride solution (20ml) and stirred for 15 min. The organic layer was then separated and washed with brine and water (20ml each) and dried over anhydrous Na_2SO_4. Concentration under reduced pressure and column chromatography on silica gel using 98:2 pet. ether:ethyl acetate afforded 11.66g (95%) of **3** as an yellow oil.

IR (neat): cm^{-1} 3450, 1460, 1400, 1170, 750, ^1H-NMR($CDCl_3$): δ 0.77-0.84 (d, 3H), 0.86-1.00 (m, 6H), 1.05-1.15 (m, 1H), 1.47-1.74 (m, 5H), 1.75-1.98 (m, 3H), 2.41 (s, 1H), 6.22-6.30 (dd, 1H), 6.33-6.43 (dd, 1H), 7.33-7.40 (dd, 1H); MS: m/z 222 (M^+, 8%), 154(6), 137(100), 123(28), 110(27), 99(40), 95(85), 86(21), 81(96), 71(81), 69(48), 55(21).

Preparation of 2-hydroxy-7-isopropyl-10-methyl-1-oxaspiro[5.5]undec-3-en-5-one(4)

To a stirred solution of **3** (3g, 19.75mmol) in anhydrous dichloromethane (40ml) maintained around 10°C, MCPBA (5.2g, 30 mmol) was added in small portions and stirring was continued at room temperature for 5 hrs. The progress of the reaction was monitored by TLC. The mixture was then cooled to 0°C and the precipitated solid was removed by filtration. The filtrate was washed successively with 20% aqueous KI (25ml), 30% aqueous $Na_2S_2O_3$ (30ml), saturated aqueous $NaHCO_3$ (40ml) and dried over anhydrous Na_2SO_4. The solvent was evaporated and the crude product was chromatographed on silica gel using 90:10 pet. ether:ethyl acetate to yield 2.37g (74%) of **4** as a viscous liquid.

IR (neat): cm^{-1} 3400-3280, 1680, 1640, 1460, 1380, 1280, 1220; ^{1}H-NMR ($CDCl_3$): δ0.80-1.00(m, 9H), 1.02-1.32(m, 1H), 1.44-1.70(m, 4H), 1.72-2.05(m, 3H), 2.20-2.35(m, 1H), 3.25-3.40(br, 1H), 5.65-5.80 (m, 1H), 6.05-6.17(dd, 1H), 6.79-6.90(dd, 1H); ^{13}C-NMR ($CDCl_3$): δ 201.27, 200.55, 147.69, 143.64, 128.21, 126.48, 87.54, 87.28, 85.70, 47.46, 46.25, 46.17, 39.94, 34.71, 29.66, 29.40, 27.90, 26.97, 23.76, 22.21, 22.15, 22.08, 19.76, 19.53; MS: m/z 238 (M^+, 5%), 155(18), 137(20), 111(8), 95(34), 84(100), 81(51), 69(14), 55(8).

Preparation of (6S,7S,10R)-7-Isopropyl-10-methyl-1-oxaspiro[5,5]undec-3-ene-2,5-dione(5)

To an ice cold stirred solution of **4** (2.25g, 9.5 mmol) in acetone (40ml), was added Jones' reagent (2.5ml) dropwise. After stirring for an additional 30min. the inorganic materials were filtered off. The filtrate was concentrated on rotavapor and partitioned between ether (75ml) and water (50ml). The organic layer was separated, washed with water (3x20ml) and dried over anhydrous Na_2SO_4. Removal of the solvent and subsequent column chromatography on silica gel using 96:4 pet.ether:ethyl acetate yielded 2.2g (97%) of the product (**5**). It was further recrystallized from *n*-hexane to give the compound as yellow needles.

$[\alpha]_D^{25}$ -53.34(c=10, $CHCl_3$); m.p.: 107°C; UV(MeOH): λ_{max} 360 nm; IR (Nujol): cm^{-1} 1730, 1690, 1630, 1470, 1380, 1320, 1260, 1250; ^{1}H-NMR ($CDCl_3$): δ0.85 (d, 3H), 0.90(d, 3H), 0.93 (d, 3H), 0.98-1.15(m, 1H), 1.31-1.48(t, 1H), 1.52-1.75(m, 3H), 1.78-2.05(m, 4H), 6.73(d, 1H), 6.88(d, 1H); ^{13}C-NMR ($CDCl_3$): 197.30, 160.80, 137.62, 134.79, 93.76, 47.97, 46.84, 34.09, 29.45, 27.05, 23.66, 21.81, 21.44, 18.87; MS: m/z 236 (M^+, 15%), 218(18), 203(16), 190(15), 175(16), 153(22), 137(100), 126(88), 109(50), 99(28), 96(31), 95(88), 91(26); Analysis: $C_{14}H_{20}O_3$: Calculated: C 71.18%, H 8.47%; Found: C 71.13%, H 8.41%.

General procedure for Diels-Alder reaction

To a stirred solution of **5** (1g, 4.23 mmol) in dry toluene was added cyclopentadiene **6a** (0.6g, 8.46 mmol) and the solution was cooled to 0°C. 6.35ml of 1M solution of Et_2AlCl in toluene was added dropwise to the above solution and the reaction mixture was stirred for 3 hrs. followed by dropwise addition of saturated NH_4Cl (50ml) and stirring for 10 min. The organic layer was separated and the aqueous layer extracted with 20ml of ether. The combined organic extracts were washed with brine and dried over anhydrous Na_2SO_4. Concentration on rotavapor and column chromatography on silica gel using 93:7 pet.ether:ethyl acetate yielded 1.23g (96.11%) of **7a**. It was further recrystallized using pet.ether to give colourless crystals.

7a: $[\alpha]_D^{25}$ -61.3(c=10, $CHCl_3$); m.p.: 154°C; IR (nujol): cm^{-1} 2910, 2860, 1750, 1710, 1460, 1380, 1240; ^{1}H-NMR ($CDCl_3$): δ0.80-0.90(m, 9H), 1.25-1.80(m, 1H), 3.02-3.12(dd, 1H), 3.35-3.45(dd, 1H), 3.57 (bs, 1H), 3.65(bs, 1H), 6.16-6.21(m, 1H), 6.30-6.36(m, 1H); ^{13}C-NMR ($CDCl_3$): 210.05, 169.84, 137.36, 136.89, 94.24, 49.95, 49.62, 49.27, 49.09, 48.92, 44.52, 42.97, 34.12, 28.82, 26.50, 23.81, 21.99, 20.72, 18.08; MS: m/z 302 (M^+, 0.8%), 274(0.5), 236(2), 148(42), 120(100), 91(71), 55(55); Analysis: Calculated: C, 75.50% H, 8.60%; Found: C, 75.54% H, 8.63%

7b: $[\alpha]_D^{23}$ -41.84 (c=5, $CHCl_3$); m.p.: 134°C; IR (nujol): Cm^{-1} 1740, 1730, 1450, 1380, 1280, 1260, 1240; ^{1}H-NMR ($CDCl_3$): δ0.85-0.95(m, 9H), 1.53-1.70(m, 12H), 1.70-1.88(m, 7H), 2.92-3.02(q, 1H), 3.14-3.25 (q, 1H); ^{13}C-NMR ($CDCl_3$): 209.83, 171.21, 123.32, 122.78, 93.59, 49.63, 46.13, 44.64, 38.16, 34.20, 30.67, 28.65, 28.50, 26.84, 23.62, 21.85, 19.86, 18.88(2C), 17.43;

7c: Colourless solid, m.p.: 100-102°C; IR ($CHCl_3$): cm^{-1} 1745, 1720. 1465, 1380, 1280, 1240; ^{1}H-NMR ($CDCl_3$): δ0.85-1.00(m, 9H), 1.35(d, 3H), 1.52-1.90(m, 13H), 2.30-2.50(m, 2H), 3.06(td, 1H), 3.25-3.40 (m, 1H), 5.35(d, 1H); ^{13}C-NMR ($CDCl_3$): 209.33, 172.25, 128.61, 126.19, 92.63, 50.18, 47.90, 45.05, 40.98, 34.27, 30.94, 29.61, 28.27, 26.88, 23.44, 23.06, 21.93, 19.79, 18.09, 17.41

7d: Viscous liquid; IR ($CHCl_3$): cm^{-1} 1745, 1735, 1715, 1450, 1365, 1325, 1205; ^{1}H-NMR ($CDCl_3$): δ0.72 (d, 3H), 0.80-0.88(m, 6H), 1.45-1.67(m, 3H), 1.70-2.05(m, 4H), 2.28-2.52(m, 4H), 2.56(d, 1H), 2.63(t, 1H), 2.75(t, 1H), 2.82-2.88(m, 1H), 2.95(t, 1H), 3.02(t, 1H); ^{13}C-NMR ($CDCl_3$): 207.01, 206.78, 168.93, 94.40, 46.84, 46.13, 42.50, 41.55, 40.63, 38.71, 33.86, 29.31, 26.99, 23.90, 23.79, 21.63, 20.12, 17.40

Cleavage of the Diels-Alder adduct 7a

To a suspension of LAH (0.251g, 6.63 mmol) in THF (100ml) was added a solution of **7a** (1g, 3.31mmol) in dry THF at room temperature. The reaction mixture was refluxed for 3 hrs. and subsequently quenched with ethyl acetate followed by dropwise addition of water. The upper liquid layer was decanted and the separated solid was removed. The organic layer was separated and the aqueous layer was extracted repeatedly with ether (3x25ml). The combined extracts were washed with brine and dried over anhydrous Na_2SO_4. Concentration on rotavapor and column chromatography on silica gel using 88:12 pet.ether:ethyl acetate yielded 0.89g (87%) of **8** as a white solid. It was further recrystallized using 98:2 pet. ether:ethyl acetate to give colourless crystals.

$[\alpha]_D^{27}$ -13.8(c=5, $CHCl_3$); m.p.: 114°C; IR (Nujol): cm^{-1} 3350, 2950, 1465, 1445, 1220; ^{1}H-NMR ($CDCl_3$): δ0.80-0.95(m, 9H), 1.32-1.80(m, 11H), 2.58-2.65(m, 3H), 2.76(bs, 1H), 3.05(bs, 1H), 3.65-3.83(d, 2H), 5.97-6.05(m, 1H), 6.20-6.28(m, 1H); ^{13}C-NMR ($CDCl_3$): 136.10, 134.50, 77.51, 63.50, 49.68, 47.50, 46.79, 46.22, 46.13, 45.79, 35.07(2C), 28.35, 25.69, 23.63, 22.83, 20.60, 18.41(2C); MS: m/z 308 (M^+, 1%), 167(1.34), 155(92), 137(40), 124(21), 106(12), 95(55), 81(100), 69(52), 55(42).

Cleavage of the triol 8

To a stirred solution of triol **8** (0.5g, 1.62mmol) in dry benzene was added lead tetraacetate (0.899g, 2.03mmol) portionwise at 0°C. The reaction mixture was stirred for an additional 5 min. The precipitate formed was filtered and the benzene solution was concentrated. Column chromatography on silica gel using 85:15 pet.ether:ethyl acetate gave 0.21g (83.46%) of optically pure menthone and 0.195g (79.26%) of the lactol **9** as a colourless viscous liquid.

$[\alpha]_D^{25}$ +23.44 (c=2.5, $CHCl_3$); IR ($CHCl_3$): cm^{-1} 3390, 2900, 2870, 1251, 1085, 1045, 995; ^{1}H-NMR ($CDCl_3$): δ1.30-1.45(m, 2H), 2.80-3.02(m, 4H), 3.38-3.45(dd, 2H), 3.90-4.00(q, 1H), 4.95(s, 1H), 6.02-6.09 (m, 1H), 6.14-6.20(m, 1H); ^{13}C-NMR ($CDCl_3$): 136.29, 135.51, 65.06, 55.45, 46.91, 44.30(2C), 44.20, 43.71; MS: m/z 152 (M^+, 2%), 135(4), 122(3), 105(3.8), 91(15.4), 66(100).

Acknowledgements: *We are grateful to Dr. T. Ravindranathan, Head, Organic Chemistry, Technology Division for encouragement and support. Our sincere thanks are due to UGC, New Delhi for fellowship to one of us (CUD).*

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(*Received in UK* 21 *August* 1995; *accepted* 23 *October* 1995)