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Catalytic Asymmetric Diels-Alder Reactions of 2-Pyrone Derivatives.¶

István E Markó,* Graham R Evans and Jean-Paul Declercq[1]

Université Catholique de Louvain, Département de Chimie, Laboratoire de Chimie Organique, Place Louis Pasteur 1, B-1348 Louvain-La-Neuve, Belgium.

¶ Dedicated fondly and with deep respect to Professor K Barry Sharpless

Abstract: *Cycloaddition reactions between the chiral 2-pyrone derivatives 9 and various dienophiles, catalysed by lanthanide shift reagents, afforded diastereomerically pure bicyclic lactones 3. A catalytic asymmetric version of these reactions, using optically active lanthanide catalysts, was successfully investigated.*

Tandem and cascade processes[2] are useful synthetic reactions which allow the regio- and stereo-controlled formation of several carbon-carbon bonds and/or ring systems in a single operation. This important strategy is ideal for the efficient assembly of complex organic molecules. We have recently described the Tandem Pericyclic Reaction (TPR) of 2-pyrone **1** with α,ω-dienes **2** affording polycyclic structures such as **4** in good yields (Figure 1).[3,4]

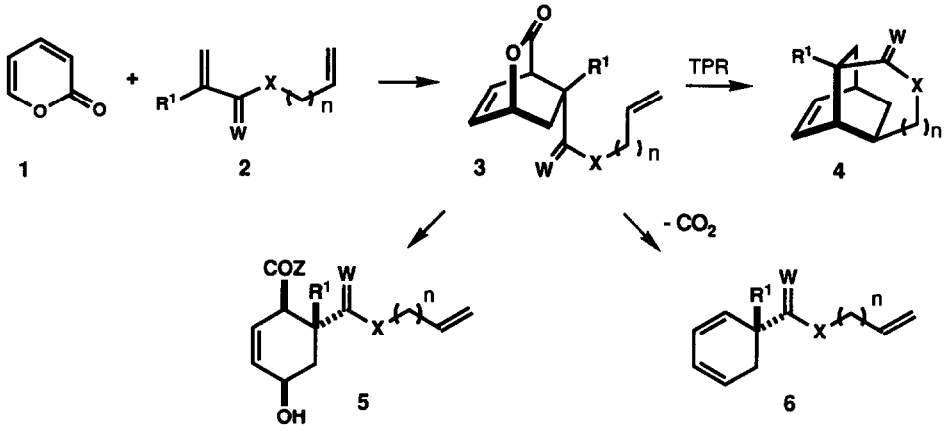


Figure 1

R[1] = H, CH_3; **W** = H, O; **X** = O, CH_2, NR; **n** = 0, 1; **Z** = OR, NR_2

This overall transformation proceeds *via* the sequence: Intermolecular Diels-Alder cycloaddition, CO_2 extrusion and intramolecular Diels-Alder reaction. We have shown that the bicyclic lactone **3** was not only a stable and isolable intermediate which could be transformed into the polycycle **4** by heating at 220-275°C but also possessed a rich chemistry of its own.[5] For

example, opening of the lactone function of **3** delivers a trisubstituted cyclohexene unit **5** which can be further elaborated stereospecifically into a variety of highly oxygenated cyclohexane derivatives.[5-7] Treatment of the primary adduct **3** with heat[8] or Lewis acids[9] promotes the loss of CO_2 without concommittant intramolecular cycloaddition and produces functionalised cyclohexadienes **6**, analogous to those obtained by microbial oxidation of aromatics.[10] The overall transformation of **1** to **6** represents one of the shortest routes to these compounds in racemic form.

A further dimension would be added to the synthetic utility of this methodology if optically active products **5** and **6** could be produced. This challenge was tackled in two different ways: (1) By using chiral esters of the 2-pyrone derivative **7** and (2) By employing asymmetric Lewis acid catalysis. In this Article, we report on some of our most recent observations in these two areas.

Earlier work in our laboratory demonstrated that 3-carbomethoxy-2-pyrone (3-CMP) **7** was a more reactive diene than 2-pyrone,[11] undergoing [4+2] cycloadditions with a range of enol ethers at atmospheric pressure and moderate temperatures (~70-80°C).[12] This reaction is also highly stereoselective, producing almost exclusively the *endo*-adduct **11** (R*=Me).[13] Furthermore, it was also discovered that certain Lanthanide-based shift reagents - amongst which $Eu(hfc)_3$ proved to be an excellent candidate - catalysed these Inverse-Electron Demand Diels-Alder (IEDDA) cycloadditions[14] **without promoting the subsequent decarboxylation reaction**, thus allowing us to produce the bicyclic lactones in excellent yields and under mild conditions (≤20°C). The ester function also proved to be a suitable vehicle to append chiral auxiliaries.

The required homochiral 3-CMP derivatives **9a-9d** were easily obtained by esterification of the acid **8**, itself readily prepared by acid-catalysed hydrolysis of 3-CMP (Figure 2).[15]

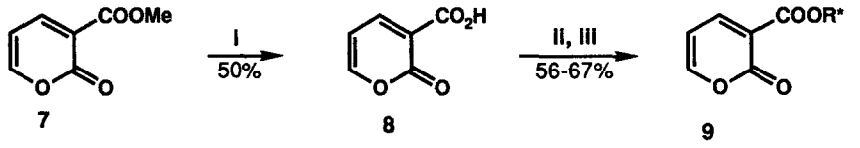
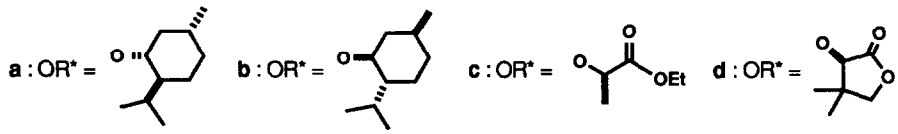
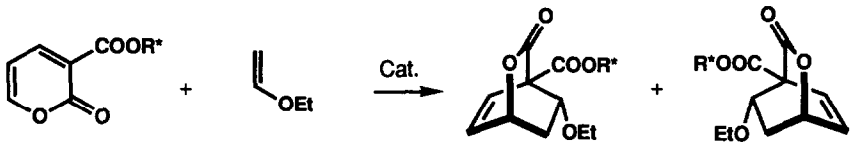


Figure 2 I = aq.HCl, 40-45°C ; II = $SOCl_2$, reflux ; III = R*OH, CH_2Cl_2, Et_3N



The diastereoselectivity of the Diels-Alder reaction of the chiral 3-CMP derivatives **9a - 9d** was then investigated, using ethyl vinyl ether as the dienophile and $Eu(hfc)_3$ as the catalyst. A selection of the most significant results are summarised in Table 1.

Table 1. Diastereoselective Reaction of **9** with Ethyl Vinyl Ether



9 **10** **11** **12**

Entry	Pyrone	Catalyst[a]	Yield[b]	d.e.[c]
1	7	(+)-Eu(hfc)$_3$	88%	<5%[d]
2	9a	-	87%	9%[e]
3	9a	(+)-Eu(hfc)$_3$	83%	28%
4	9b	(+)-Eu(hfc)$_3$	85%	8%
5	9c	(+)-Eu(hfc)$_3$	82%	61%
6	9d	-	95%	48%[e][f]
7	9d	(+)-Eu(hfc)$_3$	97%	>95%
8	9d	Eu(fod)$_3$	94%	>95%
9	9d	(-)-Eu(hfc)$_3$	91%	>95%

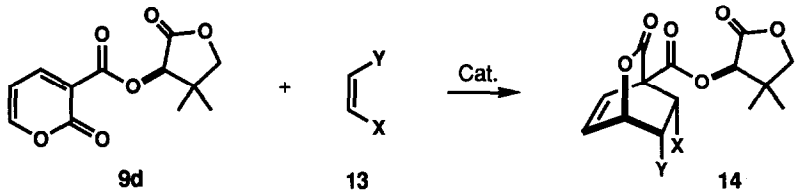
(a) 0.1 eq of catalyst used unless otherwise indicated ; **(b)** All yields refer to pure, isolated material ; **(c)** Measured by ^{13}C NMR and/or ^{1}H NMR ; **(d)** Enantiomeric excess ; **(e)** A temperature of 70°C is required in this case. All other reactions were performed at room temperature ; **(f)** Diastereoisomer **12** is the major isomer produced.

In order to measure the intrinsic facial preference displayed by the Lanthanide reagent, 3-CMP was reacted with ethyl vinyl ether in the presence of (+)-$Eu(hfc)_3$. The adduct obtained was essentially racemic (Entry 1). However, using the (l)-(-)-menthol-derived 2-pyrone **9a** and the

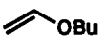
same Lanthanide catalyst, the adduct **11a** was produced with a diastereoselectivity of 28% (Entry 3). That this was the result of the matching influences[16] of the Lanthanide and the pyrone **9a** is clearly revealed in Entry 4. Indeed, employing the mismatched pair of reagents (+)-Eu(hfc)$_3$ + **9b** (now containing the (d)-(+)-menthol ester) led to a significant reduction in the observed diastereoselectivity.

The sudden increase in d.e. obtained with the lactate-based 2-pyrone **9c** provided the first indication that a third carbonyl function might play a crucial role in attaining high levels of diastereocontrol (Entry 5). Posner has reported earlier a unique example of the diastereoselective cycloaddition of 2-pyrone-(*S*)-lactate **9c** (methyl ester instead of ethyl ester) with benzyl vinyl ether, affording the bicyclic lactone product in up to 96% d.e.[17] The obtention of high levels of diastereocontrol proved to be strongly dependent not only upon the correct stereochemical matching of the pyrone derivative and the lanthanide catalyst but also upon the nature of the Lewis acid and a careful control of the reaction conditions.

Table 2. Lanthanide-Catalysed Diastereoselective Diels-Alder Reaction of **9d**



9d **13** **14**

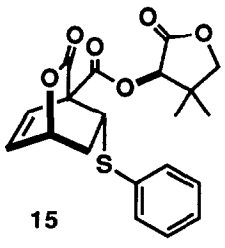
Entry	Substrate	Catalyst[a]	Yield[b]	d.e.[c]
1		Eu(fod)$_3$	94%	>95%
2		(+)-Eu(hfc)$_3$	84%	>95%
3		Eu(fod)$_3$	95%	>95%
4		(+)-Eu(hfc)$_3$	91%	75%[d]
5		(+)-Eu(hfc)$_3$	96%	~5%

(**a**) 0.1eq of catalyst used unless otherwise indicated ; (**b**) All yields refer to pure, isolated material ; (**c**) Measured by ^{13}C NMR and/or ^{1}H NMR ; (**d**) After one crystalisation from petrol/CCl_4, a d.e. >95% is obtained.

By using pantolactone as the chiral auxiliary,[18] excellent levels of diastereocontrol were finally realised at room temperature and using simple reaction conditions (Entry 7). In contrast to the results obtained using the menthol-containing reagents **9a** and **9b**, the powerful inducing ability of the pantolactone auxiliary overrides the influence of the chiral metal catalyst. Indeed, IEDDA of **9d** in the presence of either (+)-Eu(hfc)$_3$ or (-)-Eu(hfc)$_3$ results in the formation of the same diastereoisomer **11d** in >95% d.e. (Entries 7 and 9). Finally, identical levels of stereoselection were realised using **9d** and the achiral Lanthanide Eu(fod)$_3$ (Entry 8). Although the sense of asymmetric induction is dictated by the chiral auxillary, the presence of the Lewis acids **is crucial** if high diastereomeric excesses are desired, as evidenced by the poor d.e. obtained without them (Entries 2 and 6). **Remarkably, the major diastereoisomer produced using Lanthanide catalysis corresponds to the minor isomer obtained under thermal conditions** (Entries 6 and 7).[18]

Having demonstrated that **9d** provided excellent diastereoselectivity in the Lanthanide-catalysed IEDDA reaction with ethyl vinyl ether, the cycloaddition of **9d** with other dienophiles was investigated under these optimised conditions. The results are summarised in Table 2.

Except for Entry 5, where no diastereoselection was observed, good to excellent diastereomeric excesses were obtained. In all cases, the major diastereoisomer produced is the same. The absolute structure of the major diastereoisomer was unambiguously determined by single crystal X-ray diffraction analysis of **15** (**14**: X=SPh, Y=H) and is shown in Figure 3.



15

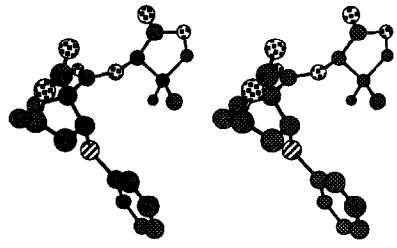


Figure 3

The facial selectivity of these cycloadditions can be rationalised by invoking the chelated structure **A** (figure 4). Attack of the dienophile on the Re face of this complex leads to the observed stereochemistry of the final adduct. However, complex **A** is not the major one formed in solution when (+)-Eu(hfc)$_3$ or Eu(fod)$_3$ is added to the 2-pyrone **9d**. Indeed, comparison of ^{1}H NMR spectra between coordinated 3-CMP, coordinated **9c** and coordinated **9d** shows that the Europium reagent mostly forms the 6-membered ring chelate **B**. For example, the chemical shift and $\Delta\delta$ values for H_4, H_5 and H_6 of 3-CMP+Eu(hfc)$_3$, **9c**+Eu(hfc)$_3$ and **B** are essentially equivalent (e.g. **9c**+Eu(hfc)$_3$: H_4: δ=7.87ppm, $\Delta\delta$=0.168; H_5: δ=6.59ppm $\Delta\delta$=0.209; H_6: δ=8.70ppm, $\Delta\delta$=0.464). We believe that this complex is in dynamic equilibrium with **A** and that **A** is the most reactive complex.

This observation is based upon the difference in reaction rates between 3-CMP and **9d** with ethyl vinyl ether, in the presence of $Eu(hfc)_3$. The pantolactone-containing 2-pyrone **9d** reacts at least 6 times faster than 3-CMP. Since 3-CMP coordinates to $Eu(hfc)_3$ to form a complex analogous to complex **B**, similar rates of reaction were expected. Coordination to the pantolactone carbonyl and formation of the seven-membered chelate **A** activates the 2-pyrone towards IEDDA reaction, resulting in the observed increase in rate. Examination of complex **A** also reveals that the Re face is most likely to be exposed to the incoming reagent. Indeed, dipole-dipole repulsions should strongly destabilise the alternative conformation **C** in which the Si face is now accessible. The facial discrimination can then be ascribed to the axial α-methyl group which efficiently shields the Si face of the 2-pyrone in complex **A** (Figure 4).[19]

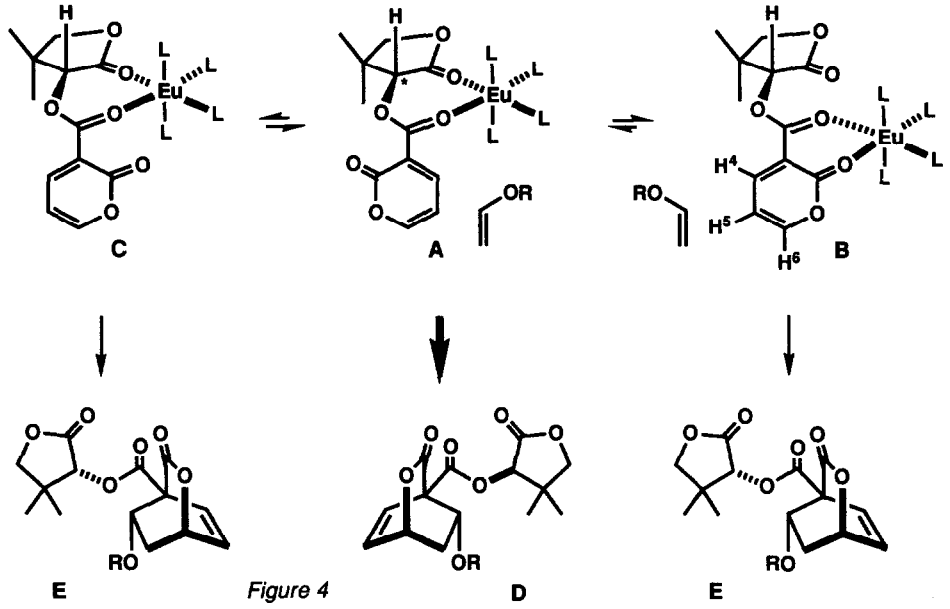


Figure 4

Interestingly, such a model also rationalises the observation that an achiral shift reagent produces equally high levels of diastereoselectivity. Indeed, the role of the Lanthanide in this model appears to involve solely the formation of the rigid seven-membered ring chelate. The absolute chirality at carbon(*) dictates which of the two seven-membered rings will be formed. The rigidity of the chelate then ensures that the α-methyl group blocks the Si face of the pyrone ring. In this model, the ligands on the metal are too far away for significant interaction with the pyrone ring and their influence is minimal, as observed experimentally. In the absence of the Lanthanide, the unchelated conformations **F** and **G** should be considered. The sterically and

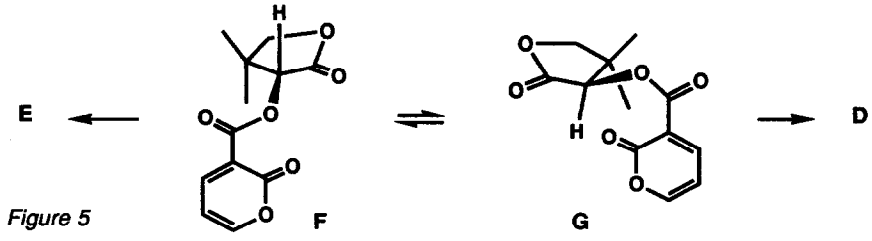
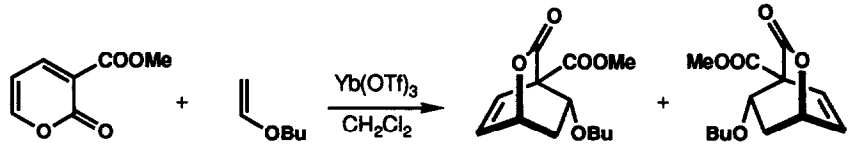


Figure 5

electronically favoured conformer **F** leads to the major diastereoisomer **E** having opposite stereochemistry to the isomer produced using the Lewis acid catalysis.

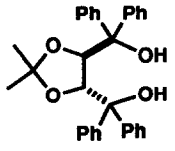
Table 3. Enantioselective Diels-Alder Reaction Catalysed by $Yb(OTf)_3$.

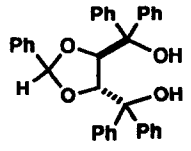


7 16 17 18

Entry	Diol	Amine	Yield[a][b]	ee[c]
1	(R)-(+)-Binol	Bu_3N	95%	31%[d]
2	(R)-(+)-Binol	$^iPr_2NEt$	95%	36%
3	(R)-(+)-Binol		93%	31%
4	TADDOL-A	$^iPr_2NEt$	56%	<5%
5	TADDOL-B	$^iPr_2NEt$	85%	<5%
6	(l)-(-)-menthol[e]	$^iPr_2NEt$	85%	<5%

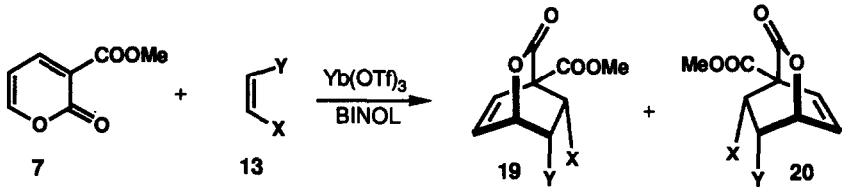
(a) All reactions performed at room temperature. **(b)** Yields are for isolated, pure material. **(c)** Determined by Lanthanide Induced Shift. **(d)** At -40°C, a lower ee of 25% is obtained. **(e)** 2 eqs of menthol added.

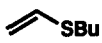
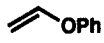
TADDOL A = 

TADDOL B = 

The key-role played by the Europium reagent in the diastereoselective Inverse Electron-Demand Diels-Alder reactions of the 3-CMP derivatives **9** prompted us to investigate the analogous enantioselective process using other lanthanides. Although early results were disappointing (with ee's below 10%), the $Yb(OTf)_3$ system reported by Kobayashi provided some hope.[20] The results of the enantioselective $Yb(OTf)_3$-catalysed IEDDA reactions of 3-CMP **7** and butyl vinyl ether are collected in Table 3.

Table 4. Enantioselective Diels-Alder Reaction of 3-CMP.



Entry	Substrate[a]	Yield[b]	Binol	ee[c]
1		90%	(R)-(+)	27%
2		93%	(R)-(+)	0%
3		70%	(R)-(+)	57%
4		91%	(R)-(+)	>95%
5		89%	(S)-(-)	86%[d]
6		11%	(R)-(+)	75%

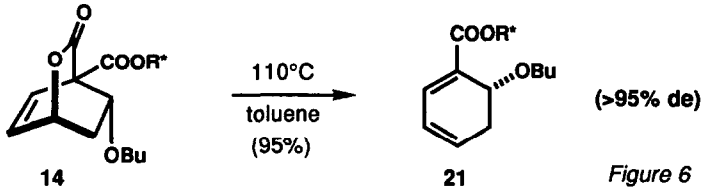
(a) 0.1eq of catalyst used unless otherwise indicated ; **(b)** All yields are for pure, isolated material ; **(c)** Measured by ^{13}C NMR and/or ^{1}H NMR ; **(d)** *(S)-(-)-Binol of less than 100% optical purity was used in this experiment.*

The initial reaction, using (R)-(+)-Binol and tributylamine, provided the expected adduct in excellent yield but in only 31% ee (Entry 1). The use of other tertiary amine bases led to

marginal improvement in the enantioselectivities, with a maximum of 36% ee being obtained with Hunig's base (Entries 2 and 3). Replacement of (R)-(+)-Binol by other diols, such as Taddol-A and Taddol-B,[21] also leads smoothly to the desired IEDDA product. **However, the adducts so produced were completely racemic** (Entries 4 and 5). Similarly racemic bicyclic lactones were obtained when (R)-(+)-Binol was replaced by (l)-(-)-Menthol (2 equivalents, Entry 6). With Binol being so far the best chiral additive, we turned our attention to other vinyl ethers and vinyl sulphides. Some pertinent results are summarised in Table 4.

As can be seen from Table 4, ethyl vinyl ether reacts as efficiently as the butyl derivative, but only modest enantiomeric excesses are observed (Entry 1). Dihydrofuran is even worse (Entry 2), giving racemic product. It is interesting to note that this enol ether is also the poorest candidate in the diastereoselective Diels-Alder reaction (Table 2, Entry 5). The surprise came when examining vinyl sulphides. Whereas the butyl vinyl sulphide/3-CMP adduct is produced with 57% ee (Entry 3), **the phenyl vinyl sulphide adduct is obtained in greater than 95% ee** (Entry 4). By using (S)-(-)-Binol, the opposite enantiomer is produced in high optical purity (Entry 5). In view of these results, phenyl vinyl ether was reacted with 3-CMP under the same reaction conditions. **An enantiomeric excess of 75% was observed for the bicyclic lactone** (Entry 6).

Although little is known about the nature of the catalytically active species in this enantiocontrolled process, we believe that several rapidly equilibrating complexes probably co-exist in solution. It is interesting to note that $Yb(OTf)_3$ **does not catalyse the 3-CMP/vinyl ether cycloaddition, even in the presence of a tertiary amine**. However, as soon as an alcohol or a diol is added, the IEDDA reaction ensues.[22]



14 21 *Figure 6*

This suggests that the enantioselective catalyst is probably more reactive than the other complexes,[23] though it is possibly a minor component of the mixture. Such a scenario would rationalise the observation that less reactive dienophiles give higher ee's. Using the highly reactive alkyl vinyl ethers, all the species in solution react rapidly with little discrimination. This results in poor enantioselectivities. However, using the less reactive phenyl vinyl sulphide or phenyl vinyl ether, the Diels-Alder reaction is now channelled through the most reactive and enantioselective complex, leading to the observed high ee's. The mechanism of

these reactions is probably more complicated and further information is required before a realistic picture emerges.

Nevertheless, the bicyclic lactones obtained are useful synthetic intermediates. When heated at 110°C, in toluene, smooth extrusion of CO_2 takes place and the optically active cyclohexadienes are produced in excellent yield and in high optical purity. An example is shown in Figure 6.

The preparation of compounds such as **21** by any other microbial or chemical route is far from obvious and would require multistep sequences. Further studies aimed at delineating the scope and utility of this methodology as well as improving the diastereo- and enantio-selectivity of the IEDDA of 2-pyrone derivatives are being actively pursued in our laboratory. The results of these studies will be reported in due course.

Acknowledgements

Financial support from the S.E.R.C. and the Université Catholique de Louvain (FDS) is gratefully acknowledged. We thank Professor John S Svendsen (University of Tromsø, Norway) for numerous stimulating discussions and for performing MM calculations on complex **A**. We would also like to thank Professor John S Svendsen and Dr Anita Maguire (University of Cork, Ireland) for obtaining some of the HRMS.

Experimental Section

General Methods. All the reactions were carried out under a dry atmosphere of argon unless otherwise stated. Melting points were obtained with a Leitz microhotstage and are uncorrected. NMR spectra were recorded using Varian XL-200 and Gemini 200 instruments, operating at 200-MHz. Chemical shifts are expressed as parts per million (δ) downfield from tetramethylsilane. Mass spectra were obtained with a Varian Matt 445 instrument, with electron impact (70eV) and chemical ionisation (100eV, ionisation gas, isobutane). IR spectra were taken with a Nicolet 500 Ft instrument. Thin layer chromatography was performed on Merck 0.2mm aluminium-backed TLC plates and visualised using ultra-violet light followed by development with alkaline $KMnO_4$ solution. Column chromatography was performed using Merck silica gel 60 (230-400 mesh) under pressure. Microanalyses were provided by the analytical department, University College London. The vinyl ethers were generally commercially available except phenyl vinyl ether, which was prepared using literature procedures.[24] Likewise the vinyl sulphides were prepared by the dehydration of the corresponding alkylthioethanols.[25]

2-Pyrone-3-carboxylic acid **8** : - The method of Kent *et al* was followed.[15] A mixture of 3-CMP (4.94 g, 0.032 mol) and 12 M HCl (15.9 ml, 0.159 mol) was heated at 40-45°C for two hours. After the usual aqueous work-up, the acid **8** was obtained in 45-67% yields. Mp = 120-122°C, lit = 122-

123°C. ^{1}H NMR (DMSO), δ_H = 13.0 (br s, 1H, CO_2H), 8.50 (dd, 1H, *J* = 2.2, 6.8 Hz, H_6), 8.31 (dd, 1H, *J* = 2.2, 4.9 Hz, H_4), 6.84 (dd, 1H, *J* = 1.8, 5.1 Hz, H_5). ^{13}C NMR (DMSO), δ_C = 164.14 (C=O), 157.86 (C_6), 148.89 (C_4), 117.43 (C_3), 106.31 (C_5). MS (EI) m/z = 140 (100), 123 (25), 112 (100), 96 (90), 95(40), 84 (65), 68 (40) 66 (25).

2-Pyrone-3-carbonyl chloride : - The above acid (1.0 g, 0.0071 mol) was refluxed with 5 mL of thionyl chloride overnight. Removal of the excess thionyl chloride under vacuum gave the crude acid chloride quantitatively. It was found to be of sufficient purity to be used crude. However, it could be bulb-to-bulb distilled at 175°C (0.1 Torr) in 89% yield. Mp = 100°C, lit = 102-103°C. ^{1}H NMR ($CDCl_3$), δ_H = 8.60 (dd, 1H, *J* = 2.1, 7.0 Hz, H_6), 7.90 (dd, 1H, *J* = 2.1, 4.8 Hz, H_4), 6.61 (dd, 1H, *J* = 2.1, 5.0 Hz, H_5). ^{13}C NMR ($CDCl_3$), δ_C = 161.21 (C=O), 158.71 (C_6) 155.18 (C=O), 153.44 (C_4), 119.85 (C_3), 106.17 (C_5). MS (EI) m/z = 160 (7), 158 (20), 126 (10), 123 (100), 112 (5), 95 (25), 68 (10).

3-Carbomenthoxy-2-pyrone ***9a*** : - The crude acid chloride (0.82 g, 5.1 mmol) in 15 mL of dry CH_2Cl_2 was added dropwise to a solution of (l)-(-)-menthol (0.80 g, 5.1 mmol) and NEt_3 (0.52 g, 0.72 mL, 5.1 mmol) in 35 mL of dry CH_2Cl_2. The reaction mixture was stirred under argon for 2 hrs. After aqueous work-up, extraction with 2 X 50 mL H_2O and drying over $MgSO_4$, the solvent was removed under vacuum. The resulting viscous oil was then bulb-to-bulb distilled to give 0.80 g (56%) of a yellow coloured viscous oil. bp = 225°C (0.1 Torr). ^{1}H NMR ($CDCl_3$), δ_H = 8.09 (dd, 1H, *J* = 2.2, 7.0 Hz), 7.65 (dd, 1H, *J* = 2.2, 5.0 Hz), 6.33 (dd, 1H, *J* = 5.08, 1.72 Hz), 4.84 (dt, 1H, *J* = 4.4 Hz), 2.05-0.92 (m, 9H), 0.86 (d, 3H, *J* = 1.0 Hz), 0.84 (d, 3H, *J* = 2.2 Hz), 0.70 (d, 3H, *J* = 6,9 Hz). ^{13}C NMR ($CDCl_3$), δ_C = 162.47 (C=O), 156.04 (C_6), 147.70 (C_4), 118.47 (C_3), 105.61 (C_5), 75.58 (CH), 46.89 (CH), 40.63 (CH_2), 34.09 (CH_2), 31.36 (CH), 26.07 (CH), 23.21 (CH_2), 21.93 (CH_3), 20.75 (CH_3), 16.13 (CH_3). IR ($CHCl_3$) ν_{max} = 3125, 2975, 2960, 2875, 1750, 1625, 1550, 1460, 1385 cm^{-1}. MS (EI) m/z = 278 (10), 247 (10), 178 (10), 141(40), 138 (100), 123 (95), 95 (80), 86 (60), 84 (70), 81 (50), 55(30). $[\alpha]_D$ = -64.7° (c = 2.96, $CHCl_3$). Accurate mass, Calcd: 278.1396, Found: 278.1399

3-Carbomenthoxy-2-pyrone ***9b*** : - The reaction was carried out as described above. After distillation, the ester **9b** was obtained in 56% yield. bp = 225°C (0.1 Torr). $[\alpha]_D$ = +62.0° (c = 2.30, $CHCl_3$)

(S)-(-)-Lactate ester ***9c*** : - Prepared as described above in 67% yield. bp = 170°C (0.1 Torr). ^{1}H NMR ($CDCl_3$), δ_H = 8.20 (dd, 1H, *J* = 2.2, 6.7 Hz, H_6), 7.68 (dd, 1H, *J* = 2.2, 5.0 Hz, H_4), 6.36 (dd, *J* = 5.1, 1.8 Hz, H_5), 5.20 (q, 1H, *J* = 7.1 Hz, CH), 4.15 (q, 2H, *J* = 7.1 Hz, OCH_2), 1.50 (d, 3H, *J* = 7 Hz, OCH_2CH_3), 1.15 (t, 3H, *J* = 7 Hz, $CHCH_3$). ^{13}C NMR ($CDCl_3$) δ_C = 170.14 (C=O), 161.79 (C=O), 156.79 (C_6), 148.89 (C_4), 116.73 (C_3), 105.68 (C_5), 69.33 (CH), 61.28 (CH_2), 13.80 (CH_3). IR ($CHCl_3$) ν_{max} = 2980, 1780, 1720, 1640, 1450, 1375, 1280, 1210 cm^{-1}. MS (EI) m/z = 240 (5), 167 (15), 154 (50), 140 (20), 126 (80), 123 (100), 95 (60), 68 (30). $[\alpha]_D$ = -6.5° (c = 1.31, $CHCl_3$). Accurate mass, Calcd: 240.075, Found: 240.0771

(D)-(-)-pantolactone ester ***9d*** : - Prepared in 66% yield after crystallisation. Mp = 97-98°C (EtOAc/CCl_4). ^1H NMR ($CDCl_3$), δ_H = 8.26 (dd, 1H, *J* = 2.3 , 6.9 Hz, H_6), 7.73 (dd, 1H, *J* = 2.2, 5.0 Hz, H_4), 6.40 (dd, 1H, *J* = 1.8, 5.1 Hz, H_5), 5.50 (s, 1H), 4.05 (s, 2H), 1.25 (s, 3H), 1.15 (s, 3H). ^{13}C NMR ($CDCl_3$), δ_C = 171.97 (C=O), 161.61 (C=O), 157.27 (C_6), 149.63 (C_4), 116.30 (C_3), 105.81 (C_5), 76.16 (CH_2), 75.87 (CH), 40.28 (C), 22.72 (CH_3), 19.78 (CH_3). MS (EI) m/z = 252 (5), 185 (5), 123 (100), 110 (5), 95 (15), 61 (10). IR ($CHCl_3$) ν_{max} = 2980, 1780, 1760, 1720, 1550 cm^{-1}. $[\alpha]_D$ = -1.34° (c = 2.96, $CHCl_3$). Anal. Calcd for $C_{12}H_{12}O_6$: C, 57.14; H, 4.80. Found: C, 56.78; H, 4.89.

General Procedure for the Thermal Diels-Alder Reaction of 3-CMP Derivatives.

Preparation of bicyclic lactones ***11a/12a*** *:* - The pyrone **9a** (58.4 mg, 0.21 mmol) and ethyl vinyl ether (0.182 g, 0.24 mL, 2.52 mmol) were dissolved in 1 mL of dry toluene and heated at 70°C overnight. TLC (petrol : EtOAc = 2 : 1) showed complete conversion of **9a** into the bicyclic lactone **11a**. The solvent and excess vinyl ether were removed under vacuum. Column chromatography on silica gel (petrol : EtOAc = 2 : 1) gave 64 mg (87%) of the *endo*-adduct **11a**. ^1H NMR ($CDCl_3$), δ_H = 6.84 (dt, 1H, *J* = 1.5, 8.0 Hz), 6.64 (dd, 1H, *J* = 5.0, 8.0 Hz), 5.29 (dq, 1H, *J* = 1.5, 7.0 Hz), 5.00 (dt, 1H, *J* = 4.1, 10.6 Hz), 4.40 (dt, 1H, *J* = 1.5, 7.0 Hz), 3.36-3.59 (m, 2H), 2.62 (m, 1H), 2.45-1.30 (m, 10H), 1.15 (t, 3H, *J* = 14.0 Hz). ^{13}C NMR ($CDCl_3$) [2 DIASTEREOISOMERS], δ_C = 168.74 (C=O), 166.62 (C=O), 130.41 (CH), 130.25 (CH), 130.08 (CH), 76.08 (CH), 74.04 (CH), 72.61 (CH), 72.33 (CH), 65.73 (CH_2), 65.12 (CH_2), 61.45 (C), 61.33 (C), 46.97 (CH), 40.62 (CH_2), 40.39 (CH_2), 35.30 (CH_2), 34.99 (CH_2), 34.11 (CH_2), 31.46 (CH), 31.37 (CH), 25.69 (CH), 25.53 (CH), 23.08 (CH_2), 22.87 (CH_2), 21.92 (CH_3), 20.82 (CH_3), 20.73 (CH_3), 15.88 (CH_3), 15.78 (CH_3), 15.09 (CH_3), 15.03 (CH_3). IR ($CHCl_3$) ν_{max} = 3040, 2970, 2950, 2940, 1765, 1750, 1610, 1360 cm^{-1}. MS (EI) m/z = 351 (10), 305 (10), 278 (20), 213 (40), 141 (50), 138 (90), 123 (100), 95 (40), 84 (55), 72 (50). Measured (^{13}C) d.e. = 9%.

Preparation of bicyclic lactone ***12d*** : - Following the procedure described above, isomer **12d** was obtained as the major diastereoisomer in 48% d.e. ^1H NMR ($CDCl_3$) δ_H = 6.76 (dt, 1H, *J* = 1.5, 8.0 Hz), 6.62 (dd, 1H, *J* = 5.0, 8.0 Hz), 5.56 (s, 1H), 5.24 (dq, 1H, *J* = 1.5, 7.0 Hz), 4.38 (dt, 1H, *J* = 1.5, 7.0 Hz), 4.03 (s, 2H), 3.48 (m, 2H), 2.59 (ddd, 1H, *J* = 4.0, 8.0, 14.0 Hz), 1.65 (dt, 1H, *J* = 2.0, 14.0 Hz), 1.26 (s, 3H), 1.15 (s, 3H), 1.07 (t, 3H, *J* = 7.0 Hz). ^{13}C NMR ($CDCl_3$) δ_C = 171.60 (C=O), 168.40 (C=O), 166.42 (C=O), 130.68 (CH), 128.85 (CH), 76.04 (CH), 75.96 (CH_2), 74.33 (CH), 72.52 (CH), 65.90 (CH_2), 61.24 (C), 40.79 (C), 35.18 (CH_2), 22.44 (CH_3), 19.47 (CH_3), 15.00 (CH_3).

General Procedure for the Europium-Catalysed Diels-Alder Reaction

3-CMP **7** (100 mg, 0.65 mmol) was added, at room temperature, to $Eu(hfc)_3$ (67 mg, 0.056 mmol, 8.6 mol%) dissolved in 2 mL of dry CH_2Cl_2. After stirring for 5 min., 0.74 mL (0.56 g, 7.7 mmol) of ethyl vinyl ether was added at once, *via* syringe. The reaction mixture was stirred at room

temperature for 6 hrs, after which time TLC (petrol : EtOAc = 2 : 1) indicated complete conversion of the 3-CMP. Evaporation of the solvent and excess vinyl ether followed by chromatography on silica gel (petrol : EtOAc = 2 : 1) gave the bicyclic lactone **11** (130 mg, 88%). This compound could be recrystallised from petrol/CCl_4. Mp = 32-33°C. ^1H NMR ($CDCl_3$), δ_H = 6.80 (dt, 1H, *J* = 1.5, 8.0 Hz), 6.62 (dd, 1H, *J* = 5.0, 8.0 Hz), 5.25 (dq, 1H, *J* = 2.0, 7.0 Hz), 4.38 (dq, 1H, *J* = 1.0, 8.0 Hz), 3.49 (m, 2H), 2.61 (ddd, 1H, *J* = 4.0, 8.0, 14 Hz), 1.69 (dt, 1H, *J* = 2.0, 14 Hz), 1.10 (t, 3H, *J* = 7.0 Hz). ^{13}C NMR ($CDCl_3$) δ_C = 168.79 (C=O), 167.61 (C=O), 130.59 (CH), 129.70 (CH), 74.22 (CH), 72.45 (CH), 65.68 (CH_2), 61.47 (C_3), 52.94 (CH_3), 35.51 (CH_2), 15.18 (CH_3). IR (neat) ν_{max} = 2980, 2950, 1760, 1740, 1620, 1450, 1360, 1280, 1195 cm^{-1}. MS (EI) m/z = 226 (10), 195 (15), 151 (20), 86 (65), 84 (100), 72 (10), 47 (25). Anal. Calcd for $C_{11}H_{14}O_5$: C, 58.40; H, 6.24. Found: C, 58.51; H, 6.38.

*Preparation of bicyclic lactone **11c*** : - Following the procedure described above, isomer **11c** was obtained with a d.e. of 61%. ^1H NMR ($CDCl_3$) δ_H = 6.78 (dt, 1H, *J* = 1.5, 8.0 Hz), 6.60 (dd, 1H, *J* = 5.0, 8.0 Hz), 5.35 (q, 1H, *J* = 12.5 Hz), 5.25 (dq, 1H, *J* = 1.5, 7.0 Hz), 4.36 (dt, 1H, *J* = 1.5, 7.0 Hz), 4.23 (q, 1H, *J* = 12.5 Hz), 3.48 (m, 2H), 2.58 (ddd, 1H, *J* = 4.0, 8.0, 14.0 Hz), 1.68 (dt, 1H, *J* = 2.0, 14.0 Hz), 1.55 (d, 3H, *J* = 7.0 Hz), 1.27 (t, 3H, *J* = 7.0 Hz), 1.08 (t, 3H, *J* = 7.0 Hz). ^{13}C NMR ($CDCl_3$) δ_C = 169.97 (C=O), 168.42 (C=O), 166.46 (C=O), 130.44 (CH), 129.77 (CH), 129.47 (CH), 74.14 (CH), 72.41 (CH), 72.23 (CH), 70.06 (CH), 69.99 (CH), 65.86 (CH_2), 61.41 (C), 61.29 (C), 35.63 (CH_2), 17.02 (CH_3), 15.12 (CH_3), 13.94 (CH_3). IR (neat) ν_{max} = 2990, 1760, 1740, 1610, 1375, 1340, 1150 cm^{-1}. Accurate mass, Calcd: 312.1209, Found: 312.1201.

*Preparation of bicyclic lactone **11d*** : - Following the procedure described above, isomer **11d** was obtained with a d.e. of >95%. ^1H NMR ($CDCl_3$), δ_H = 6.76 (d, 1H, *J* = 1.5, 8.0 Hz), 6.61 (dd, 1H, *J* = 5.0, 8.0 Hz), 5.54 (s, 1H), 5.26 (dq, 1H, *J* = 1.5, 7.0 Hz), 4.37 (dt, 1H, *J* = 1.5, 7.0 Hz), 4.04 (s, 2H), 3.47 (m, 2H), 2.57 (ddd, 1H, J = 4.0, 8.0, 14.0 Hz), 1.64 (dt, 1H, *J* = 2.0, 14.0 Hz), 1.29 (s, 3H), 1.09 (s, 3H), 1.07 (t, 3H, *J* = 7.0 Hz). ^{13}C NMR ($CDCl_3$), δ_C = 171.62 (C=O), 168.36 (C=O), 166.26 (C=O), 130.61 (CH), 129.33 (CH), 76.19 (CH), 76.02 (CH_2), 74.24 (CH), 71.85 (CH), 65.68 (CH_2), 61.72 (C), 40.71 (C), 35.33 (CH_2), 22.70 (CH_3), 19.48 (CH_3), 15.04 (CH_3). IR ($CHCl_3$) ν_{max} = 2970, 2940, 2905, 2880, 1790, 1770, 1740, 1620, 1360, 1270 cm^{-1}. MS (EI) m/z = 324 (30), 281 (10), 253 (30), 123 (100), 105 (25), 84 (25), 72 (95). $[\alpha]_D$ = -30.4 (c = 1.93, $CHCl_3$). Accurate mass, Calcd: 324.1209, Found: 324.1209.

*Preparation of bicyclic adduct **14** (X = OBu, Y = H)* : - Following the procedure described above. ^1H NMR ($CDCl_3$) δ_H = 6.78 (dt, 1H, *J* = 1.5, 8.0 Hz), 6.64 (dd, 1H, *J* = 5.0, 8.0 Hz), 5.59 (s, 1H), 5.31 (dq, 1H, J = 1.5, 7.0 Hz), 4.38 (dt, 1H, J = 1.5, 7.0 Hz), 4.09 (s, 2H), 3.49-3.42 (m, 2H), 2.61 (ddd, 1H, *J* = 4.0, 8.0, 14 Hz), 1.76 (dt, 1H, *J* = 2.0, 7.0 Hz), 1.50-1.19 (m, 4H), 1.31 (s, 3H), 0.87 (t, 3H, *J* = 7 Hz). ^{13}C NMR ($CDCl_3$), δ_C = 171.63 (C=O), 168.43 (C=O), 166.25 (C=O), 130.48 (CH), 129.41 (CH), 76.18 (CH), 76.05 (CH_2), 74.27 (CH), 72.06 (CH), 70.10 (CH_2), 61.78 (C), 40.74 (C), 35.26 (CH_2), 31.55 (CH_2), 22.72 (CH_3), 19.52 (CH_3), 19.03 (CH_2), 13.67 (CH_3). IR (neat) ν_{max} = 2970, 2940, 2870, 1790, 1760, 1740,

1620, 1470, 1370, 1270, 1100 cm^{-1}. MS (EI) m/z = 352 (10), 262 (20), 253 (70), 150 (20), 138 (20), 123 (100), 100 (40), 85 (30), 56 (30). $[\alpha]_D$ = -25.7° (c = 2.24, $CHCl_3$). Accurate mass, Calcd: 352.1522, Found: 352.1562.

Preparation of bicyclic adduct **14** *(X = SPh, Y = H)* : - Following the procedure described above, the crude bicyclic lactone was obtained with a d.e. of 75%. Recrystallisation from petrol/CCl_4 gave the diastereomerically pure product. Mp = 115.5-117°C. ^1H NMR ($CDCl_3$), δ_H = 7.48 - 7.26 (m, 5H), 6.95 (dt, 1H, *J* = 1.5, 8.0 Hz), 6.63 (dd, 1H, *J* = 5.0, 8.0 Hz), 5.50 (s, 1H), 5.31 (dq, 1H, *J* = 1.5, 7.0 Hz), 4.05 (s, 2H), 2.90 (ddd, 1H, *J* = 4.0, 8.0, 14.0 Hz), 2.05 (dt, 1H, *J* = 2.4, 14.0 Hz), 1.28 (s, 3H), 1.10 (s, 3 H). ^{13}C NMR ($CDCl_3$), δ_C = 171.55 (C=O), 168.30 (C=O), 165.70 (C=O), 133.31 (C), 132.73 (CH), 131.71 (CH), 130.46 (CH), 129.10 (CH), 128.04 (CH), 76.36 (CH), 76.05 (CH_2), 74.06 (CH), 60.23 (C), 43.09 (CH), 40.86 (C), 37.23 (CH_2), 22.70 (CH_3), 19.56 (CH_3). IR (neat) ν_{max} = 2970, 2920, 2870, 1790, 1750, 1710, 1490, 1370, 1270, 1100 cm^{-1}. MS (EI) m/z = 388 (20), 235 (10), 136 (100), 117 (30), 105 (30), 77 (10). $[\alpha]_D$ = +17.5° (c = 1.45, $CHCl_3$). Anal. Calcd for $C_{20}H_{20}O_6S$: C, 61.84; H, 5.19. Found: C, 61.60; H, 5.05.

Preparation of bicyclic lactone **14** *(X,Y = -OCH_2CH_2-)* : - Following the procedure described above. ^1H NMR ($CDCl_3$), δ_H = 6.76 (dt, 1H, *J* = 1.5, 8.0 Hz), 6.55 (dd, 1H, *J* = 5.0, 8.0 Hz), 5.54 (s, 1H), 5.23 (m, 1H), 4.83 (dt, 1H, *J* = 1.1, 8.5 Hz), 4.03 (s, 2H), 3.16 (m, 1H), 2.08 (m, 1H), 1.52 (m, 1H, 1.24 (s, 3H), 1.13-1.06 (s, 3H). ^{13}C NMR ($CDCl_3$), δ_C = 170.96 (C=O), 170.86 (C=O), 167.50 (C=O), 165.53 (C=O), 165.49 (C=O), 130.33 (CH), 129.99 (CH), 129.18 (CH), 77.11 (CH_2), 75.87 (CH), 75.70 (CH), 75.54 (CH), 75.38 (CH), 70.11 (CH), 69.91 (CH), 61.00 (C), 60.80 (C), 44.52 (CH_2), 40.18 (C), 40.10 (C), 27.28 (CH), 27.17 (CH), 21.98 (CH_3), 18.88 (CH_3). IR (neat) vmax = 2975, 2900, 2875, 1780, 1760, 1620, 1470, 1365, 1275, 1100 cm-1.

Typical Procedure for the Asymmetric Catalysed Diels-Alder Reactions of 3-CMP Using the Method of Kobayashi.

A mixture of $Yb(OTf)_3$ (62 mg, 0.1 mmol), 4A molecular sieves (125 mg) and (R)-(+)-Binaphtol (34 mg, 0.12 mmol) was cooled to 0°C under an atmosphere of Argon. Diisopropylethylamine (31 mg, 0.24 mmol) dissolved in 1 mL of dry CH_2Cl_2 was then added *via* syringe and the reaction mixture was stirred at 0°C for 30 min. After this period, 3-CMP **7** (77 mg, 0.5 mmol) dissolved in 1 mL of dry CH_2Cl_2 was added to the slightly yellow coloured mixture and an immediate orange-red colour formed. The reaction mixture was stirred at 0°C for 5 min. Butyl vinyl ether (0.21 mL, 1.5 mmol) was added *via* syringe all at once. The reaction mixture was then allowed to reach room temperature overnight. After evaporation of the solvent *in vacuo*, the crude reaction mixture was directly chromatographed on silica gel using Petrol : EtOAc = 2 : 1 as the eluant. The adducts **17+18** (0.121 g, 95%) were isolated as a slightly coloured oil. ^1H NMR using 0.1 eq $Eu(hfc)_3$ showed that an ee of 36% had been obtained. ^1H NMR ($CDCl_3$), δ_H = 6.80 (dt, 1H,

J = 1.5, 8.0 Hz), 6.20 (dd, 1H, *J* = 5.0, 8.0 Hz), 5.26 (dq, 1H, *J* = 1.5, 7.0 Hz), 4.36 (dt, 1H, *J* = 1.5, 7.0 Hz), 3.41, (m, 2H), 2.60 (ddd, 1H, *J* = 4.0, 8.0, 14.0 Hz), 1.68 (dt, 1H, *J* = 2.0, 14.0 Hz), 1.51-1.19 (m, 4H), 0.87 (t, 3H, *J* = 7.0 Hz). ^{13}C NMR ($CDCl_3$) δ_C = 168.78 (C=O), 167.61 (C=O), 130.47 (CH), 129.76 (CH), 74.23 (CH), 72.76 (CH), 69.97 (CH_2), 61.43 (C), 52.90 (CO_2CH_3), 35.36 (CH_2), 31.59 (CH_2), 19.11 (CH_2), 13.71 (CH_3). IR (neat) ν_{max} = 1765, 1740, 1620 cm^{-1}. MS (EI) m/z = 254 (10), 210 (5), 155 (100), 137 (45), 123 (65), 56 (100), 41 (70). (CI) m/z = 255 (10), 172 (10), 155 (100), 137 (30), 123 (45), 105 (50), 100 (90). FAB m/z = 255 (100), 233 (15), 167 (20).

Preparation of lactone ***19/20*** *(X = OEt, Y = H)* : - Prepared following the general procedure described above. The lactone was obtained with an ee of 27%. Mp = 32-33°C. ^{1}H NMR ($CDCl_3$), δ_H = 6.80 (dt, 1H, *J* = 1.5, 8.0 Hz), 6.62 (dd, 1H, *J* = 5.0, 8.0 Hz), 5.25 (dq, 1H, *J* = 2.0, 7.0 Hz), 4.38 (dq, 1H, *J* = 1.0, 8.0 Hz), 3.49 (m, 2H), 2.61 (ddd, 1H, *J* = 4.0, 8.0, 14 Hz), 1.69 (dt, 1H, *J* = 2.0, 14 Hz), 1.10 (t, 3H, *J* = 7.0 Hz). ^{13}C NMR ($CDCl_3$) δ_C = 168.79 (C=O), 167.61 (C=O), 130.59 (C_6), 129.70 (C_5), 74.22 (C_1), 72.45 (CH), 65.68 (CH_2), 61.47 (C_3), 52.94 (CH_3), 35.51 (CH_2), 15.18 (CH_3). IR (neat) ν_{max} = 2980, 2950, 1760, 1740, 1620, 1450, 1360, 1280, 1195 cm^{-1}. MS (EI) m/z = 226 (10), 195 (15), 151 (20), 86 (65), 84 (100), 72 (10), 47 (25). Anal. Calcd for $C_{11}H_{14}O_5$: C, 58.40; H, 6.24. Found: C, 58.51; H, 6.38.

Preparation of lactone ***19/20*** *(X,Y = -OCH$_2$CH$_2$-)* : - Prepared following the general procedure described above. The lactone was obtained in 93% yield and <5% ee. Mp = 96-97°C. ^{1}H NMR ($CDCl_3$), δ_H = 6.75 (dt, 1H, *J* = 1.5, 8.0 Hz), 6.53 (dd, 1H, *J* = 5.0, 7.9 Hz), 5.21 (m, 1H), 4.83 (dd, 1H, *J* = 1.3, 7.7 Hz), 3.89 (s, 3H), 3.87-3.66 (m, 2H), 3.14 (m, 1H), 2.09 (m, 1H), 1.52 (m, 1H). ^{13}C NMR ($CDCl_3$), δ_C = 167.50 (C=O), 166.74 (C=O), 130.70 (CH), 128.95 (CH), 77.72 (CH_2), 75.71 (CH), 69.92 (CH), 60.87 (C), 52.43 (CH_3), 44.46 (CH_2), 27.28 (CH). IR (neat) ν_{max} = 2960, 2950, 2940, 1760, 1740, 1610, 1440, 1375, 1290, 1100 cm^{-1}. MS (EI) m/z = 225 (10), 193 (10), 155 (100), 123 (60), 91 (20), 70 (80), 42 (50). Anal. Calcd for $C_{11}H_{12}O_5$: C, 58.93; H, 5.39. Found: C, 58.88; H, 5.51.

Preparation of lactone ***19/20*** *(X = SBu, Y = H)* : - Prepared following the general procedure described above. The lactone was obtained as a pink coloured oil in 92% yield and 57% ee. ^{1}H NMR ($CDCl_3$), δ_H = 6.91 (d, 1H, *J* = 7.4 Hz), 6.62 (dd, 1H, *J* = 4.8, 7.4 Hz), 5.27 (m, 1H), 3.92 (s, 3H), 3.57 (dd, 1H, *J* = 3.0, 8.8 Hz), 2.92 (ddd, 1H, *J* = 3.6, 8.0, 14.0 Hz), 2.63 (m, 2H), 1.83 (dq, 1H, *J* = 1.7, 3.0, 14.0 Hz), 1.49 (m, 4H), 0.89 (t, 3H, *J* = 7.2 Hz). ^{13}C NMR ($CDCl_3$), δ_C = 169.07 (C=O), 167.29 (C=O), 131.45 (CH), 130.80 (CH), 73.95 (CH), 59.98 (C), 52.76 (CH_3), 39.99 (CH), 38.27 (CH_2), 33.04 (CH_2), 31.69 (CH_2), 13.43 (CH_3). IR (neat) ν_{max} = 2960, 2920, 2850, 1770, 1740, 1625, 1285, 1090 cm^{-1}. MS (CI) m/z = 269 (100), 225 (10), 211 (55), 179 (30), 135 (20), 89 (10).

Preparation of lactone ***19/20*** *(X = SPh, Y = H)* : - Prepared following the general procedure described above. The lactone was obtained in 91% yield and >95% ee. Mp = 85-87°C. ^{1}H NMR ($CDCl_3$), δ_H = 7.44-7.26 (m, 5H), 7.00 (dt, 1H, *J* = 1.5, 8.0 Hz), 6.62 (dd, 1H, *J* = 5.0, 8.0 Hz), 5.26 (dq, 1H, *J* = 1.5, 7.0 Hz), 4.05 (dq, 1H, *J* = 1.0, 8.0 Hz), 3.52 (s, 3H), 2.93 (ddd, 1H, *J* = 4.0, 8.0, 14.0 Hz), 1.93

(dt, 1H, J = 2.0, 14.0 Hz). ^{13}C NMR ($CDCl_3$), δ_C = 168.69 (C=O), 166.78 (C=O), 133.44 (C), 132.61 (CH), 131.38 (CH), 130.59 (CH), 128.91 (CH), 127.91 (CH), 73.82 (CH), 59.37 (C), 52.33 (CH_3), 43.49 (CH), 36.78 (CH_2). IR (neat) ν_{max} = 1750, 1715, 1435, 900 cm-1. MS (EI) m/z = 290 (5), 151 (15), 136 (20), 86 (60), 84 (100). $[\alpha]_D$ = +92.4° (c = 1.0, $CHCl_3$). Anal. Calcd for $C_{15}H_{14}O_4S$: C, 62.05; H, 4.86. Found: C, 61.82; H, 5.03.

Preparation of lactone ***19/20*** *(X = OPh, Y = H)* : - Prepared following the general procedure described above. The lactone was obtained in 11% yield and 75% ee. ^1H NMR ($CDCl_3$), δ_H = 7.27 (t, 2H, J = 8.2 Hz), 6.99 (t, 1H, J = 7.4 Hz), 6.96 (t, 1H, J = 7.6 Hz), 6.81 (d, 2H, J = 8.2 Hz), 6.69 (dd, 1H, J = 5.2, 8.0 Hz), 5.32 (dq, 1H, J = 1.5, 7.0 Hz), 5.21 (dt, 1H, J = 1.5, 7.0 Hz), 3.84 (s, 3H), 2.79 (ddd, 1H, J = 4.0, 8.0, 14.0 Hz), 1.80 (dt, 1H, J = 1.5, 7.0 Hz). ^{13}C NMR ($CDCl_3$), δ_C = 168.10 (C=O), 166.97 (C=O), 156.41 (C), 130.77 (CH), 129.91 (CH), 129.61 (CH), 122.09 (CH), 116.05 (CH), 74.13 (CH), 71.16 (CH), 60.91 (C), 53.11 (CH_3), 35.56 (CH_2). IR (neat) ν_{max} = 2950, 1760, 1740, 1500, 1295, 1100, 1080 cm^{-1}. MS (EI) m/z = 274 (30), 220 (10), 164 (30), 133 (30), 120 (100), 94 (30), 84 (35), 77 (10).

Decarboxylation Reaction

Preparation of cyclohexadiene ***21*** : - The cycloadduct **14** (*X = OBu, Y = H*; 74.3 mg, 0.21 mmol) was dissolved in 2 mL of dry toluene and the solution was refluxed overnight. TLC (petrol : EtOAc = 2 : 1) showed the disappearance of the starting material and the formation of a new, less polar compound. Removal of the solvent gave **21** quantitatively. Due to its sensitivity, compound **21** could not be purified by chromatography on silica gel. However, the crude material was found to be >90% pure. ^1H NMR ($CDCl_3$), δ_H = 7.41 (d, 1H, J = 6 Hz), 6.32 (m, 2H), 5.54 (s, 1H), 4.48 (d, 1H, J = 6.8 Hz), 4.11 (s, 2H), 3.49 (m, 2H), 2.93 (ddd, 1H, J = 1.4, 4.6, 19.8 Hz), 2.54 (dd, 1H, J = 5.4, 19.8 Hz), 1.56-1.32 (m, 4H), 1.28 (s, 3H), 1.19 (s, 3H), 0.91 (t, 3H, J = 7.4 Hz). ^{13}C NMR ($CDCl_3$), δ_C = 172.51 (C=O), 165.96 (C=O), 137.55 (CH), 134.29 (CH), 124.68 (C), 122.68 (CH), 76.12, 75.07, 67.98, 66.85, 40.51 (C), 32.09, 30.07, 23.08, 19.96, 19.88, 19.28, 13.84 (CH_3). IR (neat) ν_{max} = 2970, 2930, 2870, 1790, 1725, 1240, 1110 cm^{-1}. $[\alpha]_D$ = +20.3° (c = 1.46, $CHCl_3$).

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