Some Unexpected Reactions Involving Diphenylketene

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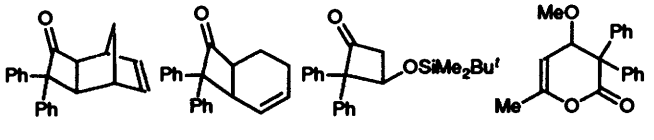
Diphenylketene reacted with the 2-azabicyclo[2.2.1]hept-5-enes **5**, **6** and **10** by attack on nitrogen to give the piperidones **7**, **8** and the cyclopentenols **11** respectively. The same ketene reacted with the cyclohexa-1,3-dienes **16** and **17** to give significant amounts of the [4 + 2] addition products **20** and **21** respectively. The initially formed product from the cycloaddition of the enol ether **23** and diphenylketene is unstable, rearranging to produce the unsaturated ester **24**.

Diphenylketene is easily prepared, is quite stable and can be purified by distillation.[1] The chemistry of this ketene has been investigated in detail.[2] For example it is known to undergo [2 + 2] cycloaddition reactions with various alkenes: norbornadiene and diphenylketene furnish the cyclobutanone derivative **1**[3] while cyclohexa-1,3-diene and the same ketene give rise to the bicyclic ketone **2**.[4] As expected the ketene reacts with the *tert*-butyldimethylsilyl ether of acetaldehyde to give the 3-trialkylsilyloxycyclobutanone **3**.[5] On some rare occasions diphenylketene has been found to undergo [4 + 2] cycloaddition reactions with the carbon–carbon double bond of the ketene acting as the dienophile. For example diphenylketene and cycloheptatriene in refluxing benzene gave 7,7-diphenylbicyclo[3.2.2]nona-2,8-diene-6-one;[6] cycloaddition of the same ketene and 4-methoxybut-3-en-2-one gave the dihydropyranone **4**.[7]

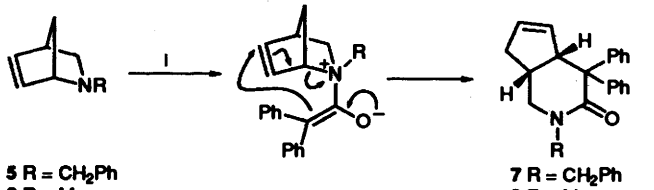
Despite this wealth of information concerning the chemistry of ketenes, in the course of some of our recent work we have found three different reactions involving diphenylketene which gave unexpected results and these reactions are described in this paper.[8,9]



1 **2** **3** **4**

Results and Discussion

In an attempt to prepare 7-azatricyclo[4.2.1.0^{2,5}]nonan-3-one derivatives, diphenylketene was allowed to react with the amines **5** and **6**.[10] The products obtained were the 2-piperidone derivatives **7** and **8** (59 and 53% yield, respectively) (Scheme 1).



5 R = CH_2Ph
6 R = Me

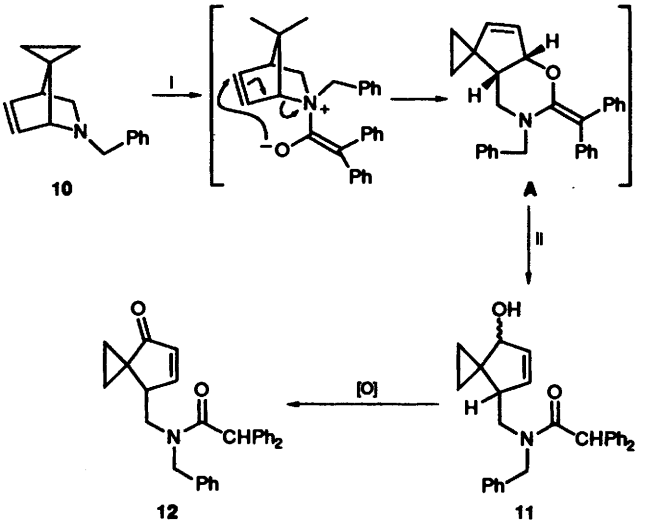
7 R = CH_2Ph
8 R = Me
9 R = H

Scheme 1 *Reagents and conditions:* i, $Ph_2C{=}C{=}O$, benzene, heat

The former compound was debenzylated to provide the parent compound **9**. Key features of the physical data for compound **7** were the position of the signal due to the carbonyl group in the IR spectrum ν/cm^{-1} 1650 and the position of the carbonyl carbon atom in the ^{13}C NMR spectrum (172.2 ppm). Other spectroscopic evidence was consistent with the structures proposed for compounds **7**–**9**.[8]

We believe the ketene attacks the amine moiety rather than the alkene unit: the reaction mechanism proposed in Scheme 1 is reminiscent of the amino-Claisen rearrangement that the amine **6** has been shown to undergo on reaction with methyl propiolate.[11] It is noteworthy that an adaptation of our newly-found ketene reaction has already been employed in a delightful synthetic sequence.[12]

Interestingly, reaction of diphenylketene with the spirocyclic compound **10** resulted in the rapid formation of a mixture of allylic alcohols **11** (51%). This mixture gave a single cyclopentenone derivative **12** on oxidation with pyridinium chlorochromate. The NMR spectra of compounds **11** and **12** were consistent with the proposed structures. Presumably the mechanism of the reaction is that described in Scheme 2. Thus,



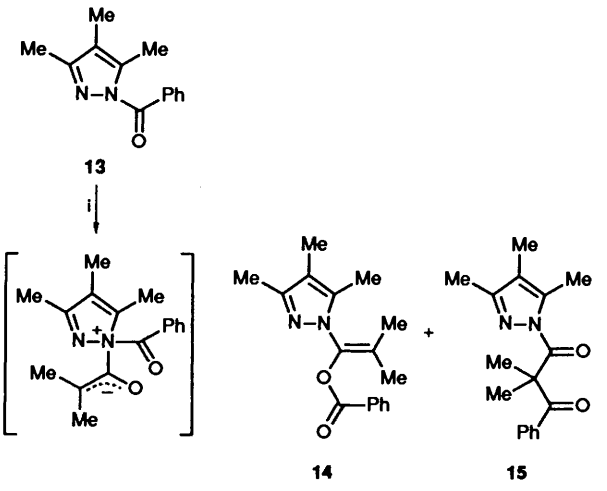
10 **A** **12** **11**

Scheme 2 *Reagents and conditions:* i, $Ph_2C{=}C{=}O$, $-50\,°C$, $CHCl_3$; ii, H_2O

the amine initially attacks the carbon atom of the carbonyl group in the ketene. Thereafter the oxyanion takes part in the rearrangement process to give an unstable tricyclic compound **A** which is attacked by water on work-up. The two epimeric alcohols **11** are formed by S_N2'-*syn* and S_N2'-*anti* reactions.

It is not clear why the presence of the spiro-cyclopropyl group should cause such a fundamental change to the course of the reaction. The considerable difference in the rate of reaction of the azanorbornenes **5** and **10** with diphenylketene cannot be explained simply by the difference in solvent polarity (benzene

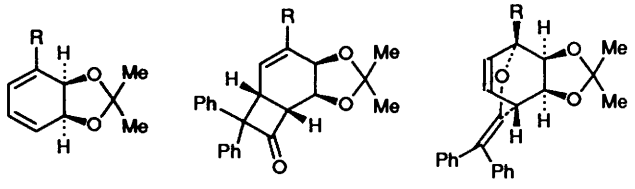
vs. chloroform) and suggests that the additional strain within the compound **10** may play a role in determining the course of the reaction. Certainly, precedents do exist for both the oxygen and carbon atoms of a coordinated ketene to act as nucleophiles: for example the *N*-benzoylpyrazole **13** forms two products **14** and **15** on reaction with dimethylketene (Scheme 3).[13]



Scheme 3 *Reagent:* i, dimethylketene

[4 + 2] Reactions involving a diene as the 4π-component and the ketene carbon–carbon or carbon–oxygen double bond as the dienophile are very rare.[14] Until recently, the latter type of reaction was believed to be confined to very sterically hindered dienes.[15] However, when the diene **16** and diphenylketene were heated under reflux in hexane for 20 h a mixture of the [2 + 2] adduct **18** and the [4 + 2] adduct **20** were formed in the ratio 3:2 (85% yield). The structure of the unexpected oxabicyclo[2.2.2]octane derivative was elucidated by IR spectroscopy (absence of a carbonyl group absorption band) and NMR spectroscopy.[9] The ketone **18** and the enol ether **20** are stable in hot tetrahydrofuran (THF) but heating either the ketone or the enol ether in octane under reflux gave **18** and **20** in the ratio 3:2 in 60–70% yield.

Even more surprising was the result of reacting diphenylketene and the fluorodiene **17** in hot THF; the enol ether **21** was formed as the major product (75% yield) while the ketone **19** was isolated in only 9% yield. However heating either the ketone **19** or the enol ether **21** in octane caused isomerization to give the cyclobutanone derivative **19** as the major component of the mixture [ratio ketone:enol ether 1.5–2:1].



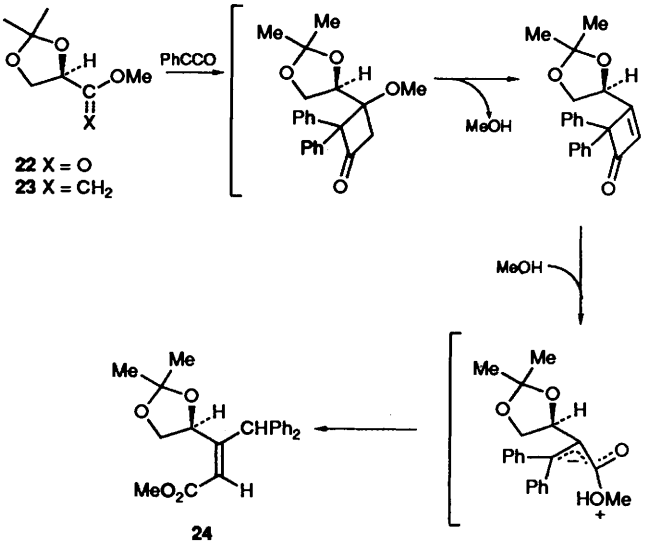
16 R = H
17 R = F

18 R = H
19 R = F

20 R = H
21 R = F

The rationale for the formation of compounds **20** and **21**, speculation concerning the 'concertedness' of the cycloaddition reaction, and the possible utility of such compounds in synthesis will be reserved until further work has been completed utilizing other ketenes and other cyclohexa-3,5-diene-1,2-diol derivatives.

The third unusual reaction involving diphenylketene was discovered as follows. Calcium (4*R*)-2,2-dimethyldioxolane-4-carboxylate is readily prepared from (±)-2,2-dimethyldioxolanylmethanol by enantioselective microbiological oxidation.[16] This calcium salt was transformed into the ester **22** using potassium fluoride and methyl iodide in dimethylformamide (87% yield). The ester **22** was treated with Tebbe's reagent[17] to give the enol ether **23** (53% yield). Reaction of this enol ether with diphenylketene gave the α,β-unsaturated ester **24** in 50% yield. In the latter reaction we propose that the first-formed product is the expected cyclobutanone (Scheme 4) which,



22 X = O
23 X = CH_2

Scheme 4

however, loses methanol readily. This alcohol attacks the carbonyl carbon atom within the highly strained cyclobutenone derivative to furnish the product. The stereochemistry about the alkene bond in compound **24** was defined by NMR spectroscopy and the observation of a nuclear Overhauser effect between the vinylic proton and the proton C*H*Ph_2.

In summary, three different reactions involving diphenylketene (**5** ⟶ **7**, **17** ⟶ **21**, and **23** ⟶ **24**) suggest that the transformations involving this cumulene can be unpredictable.

Experimental

Ethyl acetate and light petroleum b.p. 60–80 °C were distilled prior to use. Tetrahydrofuran (THF) and diethyl ether (ether) were dried by distillation from sodium metal and benzophenone prior to use. Benzene, toluene and dichloromethane were dried by distillation from calcium hydride and were stored over 4 Å molecular sieves. Dimethylformamide (DMF) was distilled from barium oxide and stored over 4 Å molecular sieves.

Thin layer chromatography (TLC) was performed on precoated glass plates (Merck silica gel 60F 254). The plates were visualised using UV light (254 nm) and/or phosphomolybdic acid in ethanol or *para*-anisaldehyde in glacial acetic acid or basic potassium permanganate, as appropriate. Flash chromatography was performed using Merck silica 60 (40–63 μm).

IR Spectra were recorded using a Perkin-Elmer 881 spectrophotometer. NMR Spectra were recorded using a Bruker AM250 spectrometer operating at 250 MHz (for ^1H spectra) or 62.9 Hz (for ^{13}C spectra). *J* Values are given in Hz.

N-Benzyl-4,4-diphenyl-1,2,4,4a,7,7a-hexahydrocyclopenta[c]*-pyridin-3-one* **7**.—*N*-Benzyl-2-azabicyclo[2.2.1]hept-5-ene (7.7 g, 0.04 mol) was dissolved in sodium dried benzene (50 cm^3) and diphenylketene (9.0 g, 0.046 mol) was added. The solution was refluxed under nitrogen for 6 d, until there was no trace of starting amine present by TLC (eluting with 30% ether in light petroleum). The reaction mixture was cooled to room temp. and quenched by the addition of methanol (10 cm^3). The

solvent was removed under reduced pressure, to give a dark brown oil, which was diluted with ethyl acetate (30 cm^3), and the product precipitated by the addition of ether (200 cm^3). Filtration at the pump resulted in a crop of tan crystals. The filtrate was reduced to a quarter of its volume under reduced pressure, and re-treated with ether, causing a second crop of product to precipitate. The process was repeated once more, and the combined crops of crystals were shown by TLC to be a single compound (R_f 0.34 in 30% ethyl acetate in light petroleum). Recrystallisation from ethyl acetate and light petroleum gave the title compound **7** (9.2 g, 59%) as a colourless, crystalline solid, m.p. 135–136 °C. The reaction was also carried out on a 5.4 × 10^{-4} mol scale in dry THF whilst immersing the sealed reaction flask in a Gallenkamp UL-150 ultrasonic bath for 12 h, to give a 61% yield of the title compound **7**, δ_H(250 MHz; $CDCl_3$) 1.90 (1 H, dm, *J* 16.5, 7-H), 2.63–2.88 (3 H, m, 1-, 7-,7a-H), 3.08 (1 H, dd, *J* 13.0 and 4.8, 1-H), 4.08 (1 H, dm, *J* 8.0, 2.0, 2.0, 2.0 and 2.0, 4a-H), 4.46 (1 H, d, *J* 14.5, CH_2Ph), 4.77 (1 H, d, *J* 14.5, CH_2Ph), 5.30 (1 H, m, *J* 5.8, 2.0, 2.0 and 2.0, 6-H), 5.70 (1 H, m, *J* 5.8, 2.0, 2.0 and 2.0, 5-H) and 7.1–7.6 (15 H, m, 3 × Ph); δ_C(62.9 MHz; $CDCl_3$) *inter alia* 34.4 (CH, C-7a); 41.7 (CH_2, C-7), 51.0 (CH_2, C-1), 51.5 (PhCH_2), 52.8 (CH, C-4a), 59.3 (C, C-4), 131.8 (CH, C-6 or C-5), 132.1 (CH, C-6 or C-5), 137.5 (C), 142.0 (C), 143.4 (C) and 172.2 (NC=O); $\nu_{max}(CH_2Cl_2)/cm^{-1}$ 3033m, 2939m, 2853m, 1650s, 1598w, 1495m and 1480m. (Found: C, 85.3; H, 6.8; N, 4.0%; $[M + H]^+$ 380.1983. $C_{27}H_{25}NO$ requires C, 85.45; H, 6.6; N, 3.7%; [M + H] 380.1983).

N-*Methyl*-4,4-*diphenyl*-1,2,4,4a,7,7a-*hexahydrocyclopenta*-[c]*pyridin*-3-*one* **8**.—*N*-Methyl-2-azabicyclo[2.2.1]hept-5-ene **6** (0.5 g, 4.6 × 10^{-3} mol) was dissolved in dry ether (10 cm^3) and cooled to 0 °C under nitrogen. Diphenylketene (1.8 g, 9.2 × 10^{-3} mol) was added over 5 min, and the reaction mixture was stirred for 3 h before being warmed to room temp., and stirred for a further 10 h. The solvent was removed, and the resulting tan oil was purified by flash chromatography, eluting with 50% ether in light petroleum, to give the *title compound* **8** (R_f 0.31) (0.74 g, 53%) as a colourless crystalline solid, m.p. 120–122 °C; δ_H(250 MHz; C_6D_6) 2.00 (1 H, dm, *J* 16.6, 4.1, 2.3, 2.3 and 3.5, 7-H), 2.20 (1 H dd, *J* 13.0, 1.2, 1-H), 2.34 (1 H, m, *J* 9.7, 4.1, 4.9, 9.6 and 1.2, 7a-H), 2.50 (1 H, m, *J* 9.7, 16.6, 2.3, 2.3 and 2.3, 7-H), 2.70 (3 H, s, NCH_3), 2.95 (1 H, dd, *J* 13.0 and 4.9, 1-H), 3.77 (1 H, m, *J* 9.6, 3.5, 2.3, 2.3 and 2.3, 4a-H), 5.26 (1 H, m, *J* 6.0, 2.3, 2.3 and 2.3, 6-H), 5.55 (2 H, m, *J* 6.0, 2.3, 2.3 and 2.3, 5-H) and 7.0–7.8 (10 H, m, 2 × Ph); δ_C(62.9 MHz; $CDCl_3$) 172.5 (C, C-3), 143.5 (C, Ph), 142.0 (C, Ph), 132.5 (CH, C-7), 132.0 (CH, C-6), 130.0 (CH, Ph), 128.5 (CH, Ph), 127.7 (CH, Ph), 127.0 (CH, Ph), 126.00 (C, Ph), 59.5 (C, C-4), 54.0 (CH_2, C-1), 52.5 (CH, C-4a), 42.5 (CH_2, C-7), 37.5 (NCH_3) and 45.0 (CH, C-7a); $\nu_{max}(CH_2Cl_2)/cm^{-1}$ 3063m, 2940m, 2852m, 1650s, 1493s, 1397m and 1351m; *m/z* (EI) 303 (41%, M^+), 237 (10%, M^+ − cyclopentadiene), 194 (100%, diphenylketene), 165 (69%, diphenylketene-C=O) (Found: M^+, 303.1623. $C_{21}H_{21}NO$ requires *M*, 303.1623).

4,4-*Diphenyl*-1,2,4,4a,7,7a-*hexahydrocyclopenta*[c]*pyridin*-3-*one* **9**.—Liquid ammonia (40 cm^3) was condensed into a dry 100 cm^3 2-necked flask, equipped with a magnetic stirrer bar, CO_2–acetone condenser and a gas inlet adapter. *N*-Benzyl-4,4-diphenyl-1,2,4,4a,7,7a-hexahydrocyclopenta[*c*]pyridin-3-one **7** (0.5 g, 1.3 × 10^{-3} mol) was dissolved in dry THF (10 cm^3), and added to the flask. Small pellets of sodium were added, until a deep blue colour persisted in the reaction mixture. The reaction mixture was stirred for a further 10 min, prior to quenching by the careful addition of anhydrous ammonium chloride. The ammonia was allowed to evaporate in a stream of nitrogen, while the reaction volume was kept constant by the addition of ether, to avoid caking of the solids present. The resulting suspension was filtered at the pump, and the solvent removed under reduced pressure, to give the title compound **9** (0.36 g, 96%) as a colourless, highly crystalline solid, which was essentially pure by ^1H NMR spectroscopy, but was re-crystallised from chloroform–light petroleum; m.p. 240–242 °C; δ_H(250 MHz; $CDCl_3$) 2.40 (1 H, m, 7-H), 2.82 (1 H, dd, *J* 13.5, 6.0, 1-H), 2.90 (2 H, m, 7a-H, 7-H), 3.05 (1 H, ddd, *J* 13.5, 4.5, 1.0, 1-H), 4.08 (1 H, m, 4a-H), 5.20 (1 H, m, *J* 5.5, 2.0, 6-H), 5.78 (1 H, m, *J* 5.5, 2.0, 5-H), 6.00 (1 H, m, 2-NH) and 7.2–7.7 (10 H, m, 2 × Ph); *m/z* (EI) 289 (48%, M^+), 223 (10%, M^+ − cyclopentadiene), 194 (100%, diphenylketene) and 165 (72%) (Found: C, 82.8; H, 6.75; N, 5.0%; M^+, 289.1466. $C_{20}H_{19}NO$ requires C, 83.0: H, 6.6; N, 4.8%; *M*, 289.1467).

7-[N-*Benzyl*-N-(*diphenylacetyl*)*aminomethyl*]*spiro*[2.4]-*hept*-5-*en*-4-*ol* **11**.—*N*-Benzylspiro(2-azabicyclo[2.2.1]hept-5-ene-7,1′-cyclopropane) **10** (0.46 g, 2.2 × 10^{-3} mol) was dissolved in anhydrous chloroform (10 cm^3) and the solution cooled to −50 °C under nitrogen. Diphenylketene (0.41 g) was then added slowly over 20 min, with virtually instant decoloration of the ketene being observed. The reaction mixture was stirred for a further 20 min. TLC (silica gel) eluting with 20% ethyl acetate in light petroleum showed the formation of a new compound, (R_f 0.27) (starting material R_f 0.07), visualised by UV and anisaldehyde. Flash chromatography in 20% ethyl acetate in light petroleum gave an amorphous powder which, after recrystallisation from ethyl acetate–light petroleum, gave the title compound **11** (0.37 g, 51%) as a colourless, crystalline solid; m.p. 110–112 °C. The NMR interpretation that follows is based on the spectrum of the mixture of isomers obtained. However, as most signals did not overlap, the data below are given for the individual isomers. Major isomer: δ_H(250 MHz; $CDCl_3$) 0.6–0.7 (3 H, m 1-H, 2-H), 0.85 (1 H, m, 1-H or 2-H), 1.70 (1 H, d, *J* 7, OH), 2.70 (1 H, m, 7-H), 3.20 (1 H, dd, *J* 13.0 and 8.5, 1′-H), 3.70 (1 H, dd, *J* 13.0 and 5.5, 1′-H), 3.97 (1 H, dd, *J* 2.3 and 7, 4-H), 4.47 (1 H, d, *J* 17, PhCH_2), 4.60 (1 H, d, *J* 17, PhCH_2), 5.05 (1 H, s, $CHPh_2$), 6.02 (1 H, ddd, *J* 6.0, 2.3 and 1.3, 5-H), 6.08 (1 H, dd, *J* 6.0 and 2.5, 6-H) and 7.25 (15 H, m, 3 × Ph); δ_C(62.9 MHz; $CDCl_3$) *inter alia* 5.1 (CH_2), 16.0 (CH_2), 49.1 (CH), 52.7 (CH_2), 54.8 (CH), 82.9 (CH), 134.1 (CH), 138.6 (CH) and 173.2 (NC=O); Minor isomer: δ_H(250 MHz; $CDCl_3$) 0.6–0.7 (3 H, m, 1-H, 2-H), 0.85 (1 H, m, 1-H or 2-H), 1.45 (1 H, d, *J* 5.0, OH), 2.48 (1 H, m, 7-H), 3.20 (1 H, obs, 1′-H), 3.40 (1 H, dd, *J* 15 and 10, 1′-H), 4.07 (1 H, dd, *J* 5.0 and 2.3, 4-H), 4.61 (1 H, d, *J* 14.5, PhCH_2), 4.81 (1 H, d, *J* 14.5, PhCH_2), 6.15 (1 H, dm, *J* 6.0, 5-H), 6.22 (1 H, dd, *J* 6.0 and 2.5, 6-H) and 7.25 (15 H, m, 3 × Ph); δ_C(62.9 MHz; $CDCl_3$) *inter alia* 4.9 (CH_2), 14.2 (CH_2), 51.6 (CH_2), 54.3 (CH), 82.7 (CH), 134.8 (CH), 138.5 (CH) and 172.4 (NC=O); $\nu_{max}(CDCl_3)/cm^{-1}$ 3694m, 3600m, 3050m, 2983m, 1641s, 1493m, 1417m and 1029m; *m/z* (EI) 424 (11%, $M + H^+$), 406 (60%, M^+ − OH), 314 [21%, $Ph_2CHCON(Bn)CH_2$], 167 (86% Ph_2CH), 120 (100%) and 91 (41%, tropylium) (Found: C, 82.0; H, 7.1; N, 3.2%; $[M + H]^+$ 424.2276. $C_{29}H_{29}NO_2$ requires C, 82.2; H, 6.9; N, 3.3%; [M + H], 424.2276).

7-[N-*Benzyl*-N-(*diphenylacetyl*)*aminomethyl*]*spiro*[2.4]*hept*-5-*en*-4-*one* **12**.—To a cold (0 °C) solution of the alcohol **11** (0.25 g, 5.9 × 10^{-4} mol) (dried under high vacuum for 3 h prior to use) in dry dichloromethane under nitrogen, was added 4 Å powdered molecular sieves (300 mg) and pyridinium chlorochromate (270 mg, 5.9 × 10^{-4} mol). The reaction was stirred vigorously at 0 °C for 30 min, and the resulting orange–brown suspension was filtered at the pump prior to flash chromatography, eluting with 55% ether in light petroleum, to give the title compound **12** (R_f 0.11) (206 mg, 83%) as a colourless, crystalline solid; m.p. 185–187 °C; δ_H (250 MHz; $CDCl_3$) 1.0–1.2

(4 H, m, 1-H, 2-H), 2.95 (1 H, dd, *J* 13.0 and 10.5, 1'-H), 3.41 (1 H, m, 7-H), 3.82 (1 H, dd, *J* 13.0 and 5.5, 1'-H), 4.35 (1 H, d, *J* 17.5, PhCH_2), 4.70 (1 H, d, *J* 17.5, PhCH_2), 5.15 (1 H, s, CHPh$_2$), 6.32 (1 H, dd, *J* 6.0 and 1.7, 6-H), 7.25 (15 H, m, 3 × Ph) and 7.62 (1 H, dd, *J* 6.0 and 2.5, 5-H); δ_C (62.9 MHz; $CDCl_3$) *inter alia* 13.4 (CH_2, C-1 or C-2), 16.7 (CH_2, C-1 or C-2), 31.2 (C, C-3), 45.7 (CH), 50.5 (CH_2), 52.9 (CH_2), 54.9 (CH), 134.2 (CH), 138.8 (C), 139.2 (C), 164.0 (CH, C[3]), 173.1 (C, *C*(O)CHPh$_2$) and 207.8 (C, C=O); $\nu_{max}(CH_2Cl_2)/cm^{-1}$ 3069m, 3033m, 2935m, 1695s, 1644s, 1584m, 1493m, 1451s and 1419m; *m/z* (EI) 314 [28%, $Ph_2CHCON(Bn)CH_2$], 167 (100% Ph_2CH), 120 (99%) and 91 (99%, tropylium) (Found: $[M + H]^+$ 422.2120. $C_{29}H_{27}NO_2$ requires M + H, 422.2120).

8,8-*Diphenyl*-4,5-*isopropylidenedioxybicyclo*[4.2.0]*oct*-2-*en*-7-*one* **18** *and* 3-(*Diphenylmethylene*)-7,8-*isopropylidenedioxy*-2-*oxabicyclo*[2.2.2]*oct*-5-*ene* **20**.—Diphenylketene (2.5 cm^3) was added to a solution of the diene **16** (1.5 g, 1.0 mmol) in dry hexane (20 cm^3) and the resultant mixture refluxed for 48 h. The reaction was quenched by the addition of water (20 cm^3) and a saturated solution of sodium hydrogen carbonate was added to give a pH of 8. The mixture was extracted with ether (3 × 20 cm^3) and the combined organic fractions were washed successively with water (50 cm^3) and brine (50 cm^3). The organic phase was dried ($MgSO_4$) and filtered. The solvent was removed by distillation at reduced pressure and the residue was subjected to flash chromatography, using as eluent ethyl acetate–light petroleum (1:15) to give the enol ether **20** (1.16 g, 33%), m.p. 153 °C, R_f 0.67 (ethyl acetate in light petroleum 1:6); ν_{max}(Nujol)/cm^{-1} 1275 (enol ether stretch); δ_H(250 MHz; $CDCl_3$) 1.33 (3 H, s, CH_3), 1.34 (3 H, s, CH_3), 3.92 (1 H, ddd, *J* 6.0, 4.0 and 2.0, 4-H), 4.45 (1 H, dd, *J* 7.0 and 4.0, 8-H), 4.61 (1 H, dd, *J* 7.0 and 4.1, 7-H), 5.11 (1 H, ddd, *J* 4.5, 4.1 and 2.0, 1-H), 6.39 (2 H, m, 5-H and 6-H) and 7.4 (10 H, br m, aryl H); δ_H(62.5 MHz; $CDCl_3$) 25.51 (CH_3), 25.56 (CH_3), 40.6 (C-4), 71.6 (C-8), 73.9 (C-7), 76.0 (C-1), 110.7 (isopropylidene C), 114.7 (C), 125.8 (aryl CH), 126.6 (aryl CH), 127.7 (aryl CH), 128.4 (aryl CH), 129.0 (C-6), 129.4 (aryl CH), 130.8 (aryl CH), 131.4 (C-5), 139.5 (aryl C), 140.9 (aryl C) and 144.9 (C-3); *m/z* (EI) 346 (M$^+$, 46%), 276 (7), 259 (3), 246 (63), 217 (5), 194 (100), 165 (95), 152 (4), 139 (5), 115 (5), 105 (2), 95 (24), 85 (2), 77 (7), 66 (6) and 51 (2) (Found: C, 79.8; H, 6.6%; M$^+$, 346.1569. $C_{23}H_{22}O_3$ requires C, 79.7; H, 6.4%; *M*, 346.1569). The more polar bicycloketone **18** was obtained as a white crystalline solid (1.81 g, 52%), m.p. 152 °C, R_f 0.58 (ethyl acetate–light petroleum 1:6); ν_{max}(Nujol)/cm^{-1} 1770 (cyclobutanone C=O stretch); δ_H(250 MHz; $CDCl_3$) 1.36 (3 H, s, CH_3), 1.40 (3 H, s, CH_3), 3.94 (1 H, dm, *J* 8.9, 1-H), 4.12 (1 H, dd, *J* 8.9 and 2.3, 6-H), 4.53 (1 H, dm, *J* 6, 4-H), 4.68 (1 H, dd, *J* 6.0 and 2.3, 5-H), 5.51 (1 H, dd, 10.7 and 3.5, 2-H), 5.65 (1 H, dm, *J* 10.7, 3-H) and 7.40 (10 H, br m, aryl H); δ_C(62.5 MHz; $CDCl_3$) 26.3 (CH_3), 28.0 (CH_3), 32.8 (C-1), 54.5 (C-6), 69.2 (C-5), 69.5 (C-4), 78.5 (C-8), 109.1 (isopropylidene quaternary C), 126.1 (C-2), 126.8 (aryl CH), 127.0 (aryl CH), 127.4 (aryl CH), 127.5 (aryl CH), 128.2 (aryl CH), 128.6 (C-3), 129.0 (aryl CH), 139.1 (aryl C), 139.9 (aryl C) and 206.0 (C-7, carbonyl); *m/z* (EI) 346 (M$^+$, 10%), 288 (5), 276 (49), 261 (6), 246 (22), 233 (6), 220 (26), 194 (97), 185 (7), 165 (100), 152 (5), 139 (5), 127 (4), 115 (7), 105 (2), 95 (21), 77 (6), 66 (2) and 51 (2) (Found: C, 79.6; H, 6.5%; M$^+$, 346, 1569. $C_{23}H_{22}O_3$ requires C, 79.7; H, 6.4%; *M*, 346.1569).

Thermolysis of 3-(*Diphenylmethylene*)-7,8-*isopropylidenedioxy*-2-*oxabicyclo*[2.2.2]*oct*-5-*ene* **20**.—Enol ether **20** (150 mg, 0.43 mmol) was dissolved in dry octane (5 cm^3) and refluxed at 130 °C for 48 h. The solvent was removed at reduced pressure to give the crude product which was purified by flash chromatography using ethyl acetate–light petroleum (1:15) as eluent. The first component isolated was the enol ether **20** as a white crystalline solid (55 mg, 37%), m.p. 153 °C, R_f 0.67 (ethyl acetate–light petroleum 1:6); the second component was the bicycloketone **18** as a white crystalline solid (81 mg, 54%), m.p. 152 °C, R_f 0.58 (ethyl acetate–light petroleum 1:6).

Thermolysis of 8,8-*Diphenyl*-4,5-*isopropylidenedioxybicyclo*-[4.2.0]*oct*-2-*en*-7-*one* **18**.—The ketone **18** (95 mg, 0.27 mmol) was dissolved in dry octane (5 cm^3) and refluxed at 130 °C for 48 h. The solvent was then removed at reduced pressure to give the crude product which was purified by flash chromatography using ethyl acetate–light petroleum (1:15) as eluent. The first component isolated was the enol ether **20** as a white crystalline solid (29 mg, 30%), m.p. 153 °C, R_f 0.67 (ethyl acetate–light petroleum 1:6) and the second component was the ketone **18** as a white crystalline solid (48 mg, 50%), m.p. 152 °C, R_f 0.58 (ethyl acetate–light petroleum 1:6).

8,8-*Diphenyl*-3-*fluoro*-4,5-*isopropylidenedioxybicyclo*-[4.2.0]*oct*-2-*en*-7-*one* **19** *and* 3-(*Diphenylmethylene*)-1-*fluoro*-7,8-*isopropylidenedioxy*-2-*oxabicyclo*[2.2.2]*oct*-5-*ene* **21**.—Diphenylketene (0.29 g, 0.3 cm^3, 1.5 mmol) was added slowly dropwise to a refluxing solution of diene **17** (0.17 g, 1.0 mmol) in dry THF (10 cm^3) for 24 h. Water (20 cm^3) was added followed by saturated aqueous sodium hydrogen carbonate to give a pH of 8. The mixture was extracted with ether (3 × 20 cm^3) and the combined organic fractions were washed successively with water (60 cm^3) and brine (30 cm^3). The organic phase was dried ($MgSO_4$) and filtered. The solvent was removed by distillation at reduced pressure and the residue was subjected to flash chromatography, using as eluent ethyl acetate–light petroleum (1:20) to give the enol ether **21** (0.28 g, 75%), m.p. 154 °C, R_f 0.81 (ethyl acetate–light petroleum, 1:6); ν_{max}(Nujol)/cm^{-1} 1272 (enol ether stretch); δ_H(250 MHz; $CDCl_3$) 1.34 (3 H, s, CH_3), 1.38 (3 H, s, CH_3), 3.82 (1 H, m, 4-H), 4.56 (2 H, br m, 7-H and 8-H), 6.38 (2 H, br m, 5-H and 6-H) and 7.32 (10 H, br m, aryl H); δ_C(62.5 MHz; $CDCl_3$) 25.4 (CH_3), 25.5 (CH_3), 40.6 (d, *J* 2.1, C-4), 75.5 (d, *J* 7.4, C-8), 78.6 (d, *J* 22.5, C-7), 111.9 (isopropylidene quaternary C), 112.9 (d, *J* 229.7, C-1), 116.2 (C), 126.3 (aryl CH), 127.1 (aryl CH), 127.8 (aryl CH), 128.5 (aryl CH), 128.8 (d, *J* 28.0, C-6), 129.4 (aryl CH), 130.6 (aryl CH), 131.4 (d, *J* 11.4, C-5), 138.4 (aryl C), 140.0 (aryl C) and 141.4 (d, *J* 5.9, C-3); *m/z* (EI) 364 (M$^+$, 15%), 264 (12), 215 (4), 194 (76), 182 (3), 165 (100), 139 (2), 113 (15), 77 (11) and 51 (7) (Found: M$^+$, 364.1475. $C_{23}H_{21}FO_3$ requires *M*, 364.1475). The more polar fluorobicycloketone **19** was isolated as a white crystalline solid (0.033 g, 9%), m.p. 125 °C, R_f 0.68 (ethyl acetate–light petroleum, 1:6); ν_{max}(Nujol)/cm^{-1} 1775 (cyclobutanone C=O stretch); δ_H(250 MHz; $CDCl_3$) 1.38 (3 H, s, CH_3), 1.46 (3 H, s, CH_3), 4.11 (2 H, m, 6-H and 1-H), 4.63 (1 H, d, *J* 6.4, 4-H), 4.83 (1 H, ddd, *J* 6.4, 1.9 and 5.6, 5-H), 5.05 (1 H, ddd, *J* 16.5, 16.5 and 2.4, 2-H) and 7.35 (10 H, br m, aryl H); δ_C(62.5 MHz: $CDCl_3$) 25.8 (CH_3), 27.7 (CH_3), 33.8 (d, *J* 7.6, C-1), 54.6 (d, *J* 2.3, C-6), 68.4 (d, *J* 23.5, C-4), 71.6 (d, *J* 6.9, C-5), 78.7 (d, *J* 3.0, C-8), 104.0 (d, *J* 18.6, C-2), 110.2 (isopropylidene quaternary C), 126.9 (aryl CH), 127.1 (aryl CH), 127.3 (aryl CH), 127.7 (aryl CH), 128.4 (aryl CH), 129.1 (aryl CH), 138.7 (aryl C), 139.5 (aryl C), 156.7 (d, *J* 260.0, C-3) and 204.6 (carbonyl, C-7); *m/z* (EI) 364 (M$^+$, 57%), 294 (4), 275 (3), 264 (18), 235 (6), 220 (32), 194 (100), 165 (92), 183 (2), 155 (2), 139 (5), 113 (12), 91 (2), 84 (4) and 63 (2) (Found: M$^+$, 364.1475. $C_{23}H_{21}FO_3$ requires *M*, 364.1475).

Thermolysis of 3-(*Diphenylmethylene*)-1-*fluoro*-7,8-*isopropylidenedioxy*-2-*oxabicyclo*[2.2.2]*oct*-5-*ene* **21**.—The enol ether **21** (10 mg, 0.03 mmol) was dissolved in dry octane (0.5 cm^3) and refluxed at 130 °C for 48 h. The solvent was then removed at reduced pressure to give the crude product which was purified by flash chromatography using ethyl acetate–light petroleum

(1:20) as eluent. The first component isolated was the enol ether **21** as a white crystalline solid (3 mg, 30%), m.p. 154 °C, R_f 0.81 (ethyl acetate–light petroleum, 1:6); the second component was the ketone **19** as a white crystalline solid (6 mg, 60%), m.p. 125 °C, R_f 0.68 (ethyl acetate–light petroleum, 1:6).

Thermolysis of 8,8-*Diphenyl*-3-*fluoro*-4,5-*isopropylidenedioxybicyclo*[4.2.0]*oct*-2-*en*-7-*one* **19**.—The ketone **19** (10 mg, 0.3 mmol) was dissolved in dry octane (5 cm^3) and refluxed at 130 °C for 48 h. The solvent was removed at reduced pressure to give the crude product which was purified by flash chromatography using ethyl acetate–light petroleum (1:20) as eluent. The first component isolated was the enol ether **21** as a white crystalline solid (4 mg, 35%), m.p. 154 °C, R_f 0.81 (ethyl acetate–light petroleum, 1:6); the second component was the ketone **19** as a white crystalline solid (5 mg, 50%), m.p. 125 °C, R_f 0.68 (ethyl acetate–light petroleum, 1:6).

Methyl (4R)-2,2-*Dimethyl*-1,3-*dioxolane*-4-*carboxylate* **22**.—Calcium (4*R*)-2,2-dimethyl-1,3-dioxolane-4-carboxylate (5.0 g, 13.02 mmol) and potassium fluoride (780 mg, 4.4 mmol) were suspended in dry dimethylformamide (10 cm^3) and iodomethane (61.01 mmol) was added. The reaction mixture was stirred under argon at room temp. for 20 h, diluted with ether (200 cm^3), washed with water (3 × 50 cm^3) and saturated aqueous sodium chloride (50 cm^3), dried (Na_2SO_4) and evaporated. The crude product was filtered through a short column of silica using ether in light petroleum (b.p. 40–60 °C) as eluent to give the ester **22** (87%); $\delta_H(CDCl_3)$ 1.41 (3 H, s, CH_3), 1.46 (3 H, s, CH_3), 3.68 (3 H, s, OCH_3), 4.00–4.38 (2 H, m, CH_2) and 4.60 (1 H, *J* 6.7 and 5.5, CH).

Preparation of the Enol Ether **23**.—The ester **22** (1 mmol) and pyridine (10 mm^3) were dissolved in toluene and THF (ratio 3:1; 2 cm^3) at −40 °C. Tebbe reagent (1.1 mmol) in toluene[17] was added dropwise; the mixture was stirred for 50 min at −40 °C and warmed to room temp. Aqueous sodium hydroxide (15% w/v; 0.3 cm^3) was added dropwise to the cooled (−10 °C) reaction mixture, whereupon the mixture was warmed to room temp. After gas evolution had ceased, the dark green solution was diluted wth ether (15 cm^3), dried (Na_2SO_4), filtered through Celite and evaporated under reduced pressure. The crude product was filtered through a short column of silica using ether in light petroleum (40–60 °C) as eluent to afford the enol ether **23**. $\delta_H(CDCl_3)$ 1.37 (3 H, s, CH_3), 1.44 (3 H, s, CH_3), 3.56 (3 H, s, OCH_3), 3.83 (1 H, dd, *J* 8.1, 6.8, HC*H*), 4.03 (1 H, d, *J* 2.35, alkene CH), 4.10 (1 H, dd, *J* 8.15, 6.7, *H*CH), 4.28 (1 H, dd, *J* 2.35, 0.7, alkene CH) and 4.43 (1 H, ddd, *J* 6.8, 6.7, 0.7, CH); $\delta_C(CDCl_3)$ 25.66 (CH_3), 26.12 (CH_3), 54.98 (OCH_3), 68.28 (OCH_2), 75.85 (OCH), 81.73 (alkene CH_2), 109.72 (OCO) and 161.31 (alkene C).

Preparation of the Ester **24**.—The enol ether **23** (35 mg) was dissolved in dry dimethylformamide (1 cm^3). Diphenylketene (172 mg) was added and the solution was stirred at room temp. under an atmosphere of argon for 16 h and then heated to reflux for 5 h. The reaction mixture was cooled and poured into saturated aqueous sodium hydrogen carbonate (20 cm^3). The aqueous phase was extracted with ether (3 × 20 cm^3). The combined organic extracts were washed with saturated aqueous sodium hydrogen carbonate (2 × 20 cm^3) and saturated aqueous sodium chloride (2 × 20 cm^3) and then dried ($MgSO_4$). Chromatography over silica using ethyl acetate in hexane (1:9→1:4) gave the ester **24** (39 mg, 50%); $\delta_H(CDCl_3)$ 1.39 (3 H, s, CH_3), 1.49 (3 H, s, CH_3), 3.61 (3 H, s, OCH_3), 3.82 (1 H, dd, *J* 8.5, 5.4, OHC*H*), 4.44 (1 H, dd, *J* 8.5, 7.2, O*H*CH), 5.55 (1 H, s, alkene CH), 5.73 (1 H, ddd, *J* 7.2, 5.4 and 0.8, OCH) and 7.23–7.42 (10, m, Ar-H); $\delta_C(CDCl_3)$ *inter alia* 25.43 (CH_3), 25.60 (CH_3), 56.28 (OCH_3), 65.15 ($CHPh_2$), 69.34 (OCH_2), 73.71 (OCH), 100.12 (alkene CH), 110.64 (CMe_2), 139.15 and 139.23 (2 × aryl C) (Found: C, 77.7; H, 6.5. $C_{22}H_{24}O_4$ requires C, 77.3; H, 6.7%).

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