Highly Stereoselective Alkylation of Spiro-γ-lactones

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Received December 10, 1996[⊗]

The alkylation of the (±)-spiro-γ-lactones **1** and **5a** occurs with high diastereofacial selectivity. Geometry-optimized *ab initio* 4-31G calculations on enol **7** suggest that electrophilic attack occurs at an angle of about 80° to the plane of the enolate, together with a displacement of the trajectory away from the oxygen linked to lithium.

In connection with our interest in steroid synthesis,[1] we have recently reported a new strategy for the preparation of 1,1-disubstituted-2,5-divinylcyclopentanes. These latter arise from addition of 1,8-bis(trimethylsilyl)-2,6-octadiene (BISTRO) to different electrophilic reagents.[2] Thus, the (±)-spiro-γ-lactone **1**, was diastereoselectively elaborated by reaction of BISTRO with succinic anhydride[3] (or 3-carbomethoxypropionyl chloride), and further involved in a very short synthesis of 17-vinyl-1,3,5(10)-gonatriene derivatives.[4] During the course of this synthesis, we showed that the alkylation of the enolate **2** with iodobenzocyclobutene led to only one stereoisomer whose structure has been confirmed by X-ray crystal diffraction analysis of the resulting steroid.[5] In this paper we examine the stereofacial selectivity of the alkylation of the enolate **2**.

During the past decade, considerable attention has been given to the stereochemistry of the alkylation of metal enolates of γ-butyrolactones.[6] It is well recognized that electrophilic attack on the enolates of β-substituted γ-butyrolactones is controlled exclusively by the β-substituent leading to the trans addition products.[7] However, Iwasaki reported the reverse diastereofacial differentiation in the alkylation of the enolates of α,β-dibenzyl-γ-butyrolactones. He proposed that the factor controlling the selectivity in this case was allylic strain.[8] Like β-substituents, γ-substituted γ-lactones also give stereoselective trans alkylation.[9]

To facilitate the discussion of the results presented below, we here summarize the accumulated data concerning enolate structure and reactivity.

(a) In weakly polar aprotic solvents, Li enolates are found to be more or less aggregated in solution.[10,11]

(b) Diisopropylamine, concomitantly generated with the Li enolate from a carbonyl compound and LDA, is known to have an effect upon the reactivity of the enolate.

(c) Attacking electrophiles must obey the principle of maximum overlap of participating orbitals by approaching perpendicular to the plane of atoms which constitute the enolate function.[12] On the basis of the accepted model for nucleophilic attack on carbonyl centers,[13] it is postulated that in the enolate HOMO, the related repulsive interaction between the electrophile LUMO and the oxygen should provoke a displacement of the electrophile trajectory away from the oxygen (angle of attack should be obtuse).[6a,14] But more recent calculations on transition structures for the aldol reactions of enolates have located cyclic transition states with an acute angle of attack.[15−17] For electrophilic additions on enols or enolates, *ab initio* calculations using the 3-21G basis set led to an optimal angle of attack of ≈80° (deviation of ±10° from the optimal value costs roughly 1 kcal/mol).[18]

(d) Alkylation of enolates is a strongly exothermic reaction and, in accord with the Hammond postulate, the

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⊗ Abstract published in *Advance ACS Abstracts,* July 1, 1997.

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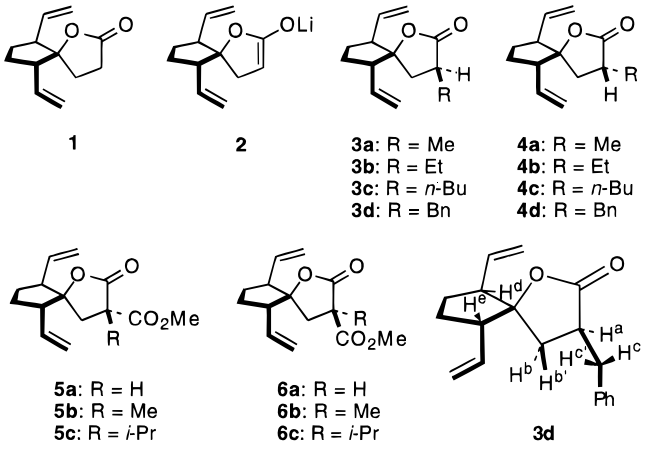
S0022-3263(96)02302-X CCC: $14.00

Table 1. Alkylation of Lactones 1 and 5a, 6a



entry	lactone	base	HMPA (equiv)	electrophile (equiv)	reactn time (h)	yield (%)	selectivity
1	**1**[a]	LDA		MeI (10)	24	30	
2			3		24	23	
3		LHMDS			1	60	**3a**:**4a** = 11.5:1
4				EtI (10)	1	55	**3b**:**4b** = 11:1
5				*n*-BuI (10)	1.5	62	**3c**:**4c** = 11:1
6				*i*-PrI (10)	24	0	
7				BnBr (10)		40	**3d**:**4d** = 12:1
8	**5a**, **6a**[b]	K_2CO_3		MeI (1.5)	20	98	**5b**:**6b** = 3:1
9				*i*-PrI (1.5)	36	62	**5c**:**6c** = 4:1
10	**5a**, **6a**[c]			MeI (1.5)	30	75	**5b**:**6b** = 3.4:1
11		Cs_2CO_3			5	100	**5b**:**6b** = 3:1

[a] Reaction conditions: THF, −60 °C. [b] Reaction conditions: acetone, reflux. [c] Reaction conditions: acetone, room temp.

transition states are largely reactant-like in character.[19] Where the enolate is substituted by an electron-stabilizing group (e.g. CO_2Me), it becomes less reactive, leading to a more product-like transition state.[20]

The alkylation of **2** with methyl iodide was examined first. The reaction was carried out in THF under standard conditions by converting lactone **1** into enolate **2** with LDA at low temperature followed by addition of the alkylating reagent (10 equiv)(in one experiment, 3 mol equiv of HMPA was added). Moderate yields of **3a**, as major stereoisomer, were obtained, but better yields were observed by the use of lithium hexamethyldisilazane (LHMDS). This result can be explained by the fact that LHMDS is sterically more hindered, less basic, and also less highly aggregated, moreover it produces the more poorly complexing $HN(SiMe_3)_2$ in the proton transfer step. Subsequently, this procedure was applied to a series of alkyl halides. The π-facial selectivity observed is in the range of 92 to 98%. No reaction was seen with secondary alkyl halides such as *i*-PrI.

The relative stereochemistry of the products **3a**−**d** was determined by a series of 1D, COSY, and NOESY experiments (400 MHz). In particular, for lactone **3d**, phase mode NOESY experiments confirmed the vicinal relationship between the benzyl group and its adjacent vinyl group. We observed, in the NOESY diagram, that H(a) (δ = 2.98, $J_{ab} = J_{ab'} = J_{ac'}$ = 9.6 Hz, J_{ac} = 4.3 Hz) only gives cross peaks with H(b) (δ = 1.91, $J_{bb'}$ = 13.4 Hz) and H(c) (δ = 3.19, $J_{cc'}$ = 14.0 Hz). The proximal position of H(b) and H(d) (δ = 2.35) was evidenced by the existence of a cross peak. On the other hand, the syn relationship between H(c′) (δ = 2.67) and H(b′) (δ = 2.01) was confirmed by a cross peak. In contrast, no cross peak has been observed between H(b′) and H(e) (δ = 2.58).

Table 2. Optimized Heat of Formation of Lactones Calculated by the PM3 and/or AM1 Methods

method	lactone	heat of formation (kcal/mol)	lactone	heat of formation (kcal/mol)	ΔH_f (kcal/mol)
PM3	**3a**	−66.95	**4a**	−67.16	0.21
AM1		−64.87		−64.81	−0.06
PM3	**3c**	−80.70	**4c**	−81.47	0.77
AM1		−83.16		−83.20	0.04
PM3	**3d**	−38.94	**4d**	−38.62	−0.32
AM1		−38.18		−37.20	−0.98
PM3	**5a**	−138.15	**6a**	−138.43	0.28
PM3	**5b**	−141.83	**6b**	−142.11	0.28
	5c	−148.18	**6c**	−149.74	1.56

In all cases, the stereoselectivity of the reaction is such that preferred attack is onto that face of the enolate which bears the vinyl group anti to the lactone ring-oxygen linkage.[21] Thus alkylation takes place on the seemingly more hindered face of the lactone.

Semiempirical calculations, PM3[22] or AM1,[23] show that the alkylated lactones **3** and their diastereomers **4** have almost the same energy (Table 2). Hence we can conclude that the explanations usually put forward to explain the stereochemical outcome of the alkylation of enolates {e.g. substrate-like versus product-like transition states or torsional strain arising from eclipsing of adjacent groups ($A^{(1,2)}$ and $A^{(1,3)}$ strains)} are of similar

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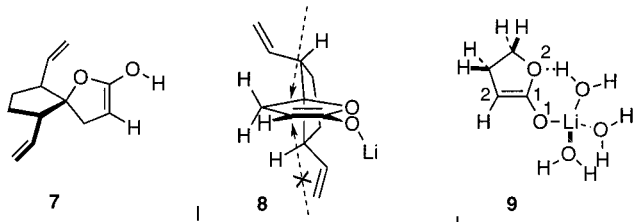
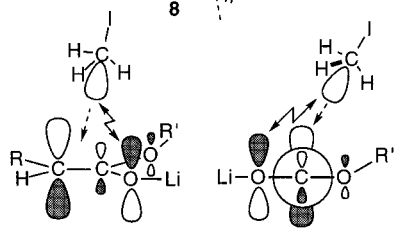
magnitude for the two directions of attack. Indeed, since both faces of the enolate **2** are identically substituted (only the relative chirality of the vinyl groups, which are far from the nucleophilic center, differentiates them) we must conclude that the facial selectivity is controlled mainly by steric interactions and not by electronic factors.

With the aim of understanding the origin of this diastereofacial selectivity, we have carried out molecular orbital calculations to determine the preferred geometry of the enol **7** and consequently the probable trajectory of the electrophilic reagent.[24] The 4-31G-optimized geometry of **7** shows that both the diastereotopic faces of the enolate are relatively accessible. However, if an angle of attack of about 80° to the plane of the enolate occurs, combined with a displacement of the electrophile trajectory away from the oxygen linked to lithium, the face containing the vinyl group anti to the lactone ring-oxygen is favored as depicted in structure **8**. In contrast, attack on the face with the vinyl group syn to the lactone ring-oxygen, should be preferred with an approach at an obtuse angle.



7 **8** **9**



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Model STO-3G calculations were performed on the enolate **9** where the lithium was encapsulated by three molecules of water as ligands. Calculations indicated that the magnitude of the HOMO coefficient at O(1) is greater than at O(2) [MP2/RHF/STO-3G; energy (au), 533.14646; HOMO (eV), −0.151; O(1), −0.565; O(2), −0.198; C(1), 0.268; C(2), 0.703; Li, −0.140]. As depicted in transition state **10**, the out-of-phase overlap between the σ*-LUMO of the electrophile and the more contributing oxygen in the HOMO (secondary orbital interaction) pushes the electrophile closer to the cyclopentane ring and increases the π-facial selectivity for acute angles of approach.

The necessity of using 10 mol equiv of alkyl halide for the substitution of **2** renders the use of elaborated benzocyclobutenyl iodides extremely inefficient. With the aim of enhancing the nucleophilic character of the enolate, **2** was acylated with dimethyl carbonate to give **5a** and **6a** (inseparable mixture, 93% yield).[25] The alkylation of methoxycarbonyl lactones **5a**, **6a** was achieved using the very simple procedure of Claisen, anhydrous potassium carbonate in refluxing acetone.[26] Alkylation with methyl iodide or isopropyl iodide occurred quantitatively using only 1.5 mol equiv of electrophile. Each of the product pairs **5b**, **6b** or **5c**, **6c** was separable by flash chromatography on silica gel. The reaction furnished **5b** or **5c** as the major compound (see Table 1) with the incoming alkyl group on the face bearing the vinyl group which is anti to the lactone ring-oxygen. Thus, the same stereochemical outcome is observed as for the alkylation of **2**. But in this instance, the lactones **5b** and **5c** are less stable than their diastereomers **6b** and **6c**, respectively, showing that the facial stereoselectivity is definitely a kinetic phenomenon.

Conclusion

Our model requires that the approach of an electrophile to an endocyclic enolate be at a slightly acute angle to the plane of the enolate with the trajectory canted away from the oxygen linked to the metal ion. This explains the observed facial selectivity for remote substituents, in particular the observations of Tomioka and Koga concerning the alkylation of endocyclic enolate.[27]

Experimental Section

General. All reactions were run under argon in oven-dried glassware. TLC was performed on silica gel 60 F_{254}. ^{1}H and ^{13}C NMR spectra were recorded in $CDCl_3$ solutions at 400, 200 and 100, 50 MHz, respectively. Carbon−proton couplings were determined by DEPT sequence experiments.[28] Lactone **1** was prepared according to our previous works.[3]

General Procedure for the Alkylation of Lactone 1. Method A. To a solution of diisopropylamine (0.111 g, 1.1 mmol, 1.1 equiv) in 5 mL of THF at −10 °C was slowly added 0.7 mL (1.1 mmol, 1.1 equiv) of a 1.6 M solution of *n*-butyllithium in hexane. The mixture was cooled to −60 °C, and a solution of lactone **1** (0.192 g, 1 mmol) in THF (2 mL) was added. Then, a solution of alkyl halide (10 mmol, 10 equiv) in 2 mL of THF was slowly added. The solution was stirred for 24 h, as the disappearance of the lactone was monitored by TLC. The reaction was quenched by addition of saturated aqueous NH_4Cl solution. After warming to room temperature, the reaction mixture was extracted with ether. The extracts were dried using $MgSO_4$ and then concentrated under vacuum. The crude product was flash chromatographed on silica gel eluting with a gradient of petroleum ether−ether.

Method B. To a solution of 1 M solution of lithium hexamethyldisilazide in hexane (1.1 mL, 1.1 mmol, 1.1 equiv) in THF (4 mL) cooled at −80 °C was added a solution of lactone **1** (0.192 g, 1 mmol) in THF (0.5 mL). After 0.5 h of stirring at −80 °C, a solution of alkyl halide (10 mmol, 10 equiv) in 2 mL of THF was slowly added. After usual workup, the lactones **3** were purified by flash chromatography on silica gel.

(3*S,6*S**,9*S**)-3-Methyl-6,9-divinyl-1-oxaspiro[4.4]nonan-2-one (3a).** Reaction of **1** and methyl iodide following method B gave **3a**: 60% yield; IR 3080, 1775, 1640 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 5.74 (ddd, J = 17.1, 10.1, 9.1 Hz, 1H), 5.57 (dt, J = 17.6, 9.4 Hz, 1H), 5.17−5.04 (m, 4H), 2.75−2.61 (m, 2H), 2.40 (dd, J = 10.6, 8.7 Hz, 1H), 2.18 (m, 1H), 2.10 ($^1/_2$AB, d, J = 13.2, 9.33 Hz, 1H), 1.92 ($^1/_2$AB, d, J = 13.2, 10.73 Hz, 1H), 1.86 (m, 1H), 1.77 (m, 1H), 1.56 (m, 1H) 1.14 (d, J = 7.21 Hz, 3H); ^{13}C NMR ($CDCl_3$) δ 179.5 (s), 137.9 (d), 135.9 (d), 118.2 (t), 117.0 (t), 94.5 (s), 54.0 (d), 53.2 (d), 36.1 (d), 35.4 (t), 29.0 (t), 28.5 (t), 15.9 (q).

(3*S,6*S**,9*S**)-3-Ethyl-6,9-divinyl-1-oxaspiro[4.4]nonan-2-one (3b).** Reaction of **1** and ethyl iodide following method B gave **3b**: 55% yield; IR 3080, 1775, 1640 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 5.60 (m, 2H), 5.05 (m, 4H), 2.45 (m, 3H),

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1.80 (m, 6H), 1.33 (m, 2H), 0.90 (d, J = 7.3 Hz, 3H); ^{13}C NMR ($CDCl_3$) δ 178.9 (s), 138.0 (d), 136.0 (d), 118.3 (t), 117.0 (t), 94.7 (s), 54.1 (d), 53.4 (d), 41.9 (d), 33.2 (t), 28.9 (t), 28.6 (t), 24.1 (t), 11.5 (q).

(3*S,6*S**,9*S**)-3-*n*-Butyl-6,9-divinyl-1-oxaspiro[4.4]-nonan-2-one (3c):** Reaction of **1** and *n*-butyl iodide following method B gave **3c**: 71% yield; IR 3090, 1775, 1640 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 5.65 (m, 2H); 5.10 (m, 4H), 2.65 (m, 2H), 2.40 (m, 1H), 1.90 (m, 6H), 1.37 (m, 6H), 0.90 (t, J = 6.7 Hz, 3H); ^{13}C NMR ($CDCl_3$) δ 179.0 (s), 138.0 (d), 136.0 (d), 118.2 (t), 116.9 (t), 94.8 (s), 54.1 (d), 53.3 (d), 40.5 (d), 33.8 (t), 31.1 (t), 29.5 (t), 28.9 (t), 28.6 (t), 22.4 (t), 13.9 (q); MS m/z 193 (9), 108 (21), 95 (12), 93 (11), 91 (12), 81 (22), 79 (17), 68 (12), 67 (24), 55 (23), 54 (47), 53 (13), 43 (10); HRMS calcd for $C_{16}H_{24}O_2$ 220.1462, found 220.1463.

(3*S,6*S**,9*S**)-3-Benzyl-6,9-divinyl-1-oxaspiro[4.4]nonan-2-one (3d):** Reaction of **1** and benzyl bromide following method B gave **3d**: 40% yield; IR 3080, 3030, 1775, 1640, 1175, 920 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.25 (m, 3H), 7.15 (m, 2H), 5.75 (ddd, J = 17.1, 10.1, 9.0 Hz, 1H), 5.50 (ddd, J = 16.9, 10.1, 9.2 Hz, 1H), 5.18−4.92 (m, 4H), 3.19 (dd, J = 14.0, 4.3 Hz, 1H), 2.98 (qd, J = 9.6, 4.3 Hz, 1H), 2.67 (dd, J = 14.0, 9.6 Hz, 1H), 2.58 (td, J = 8.7, 3.9 Hz, 1H), 2.35 (td, J = 10.1, 8.7, Hz, 1H), 2.15 (m, 1H), 2.01 (dd, J = 13.4, 10.2 Hz, 1H), 1.91 (dd, J = 13.4, 9.6 Hz, 1H), 1.85 (m, 1H), 1.74 (m, 1H), 1.51 (m, 1H); ^{13}C NMR ($CDCl_3$) δ 179.0 (s), 138.6 (s) 137.8 (d), 135.9 (d), 129.0 (d)(2C), 128.7 (d)(2C), 126.6 (d), 118.5 (t), 117.1 (t), 95.1 (s), 53.9 (d), 53.3 (d), 42.3 (t), 36.9 (d), 33.0 (t), 28.8 (t), 28.5 (t). Anal. Calcd for $C_{19}H_{22}O_2$: C, 80.82; H, 7.85. Found: C, 80.72; H, 7.90.

(3*RS*,6*S,9*S**)-3-(Methoxycarbonyl)-6,9-divinyl-1-oxaspiro[4.4]nonan-2-one (5a, 6a).** To a solution of 2.10 g (0.011 mmol, 2.2 equiv) of lithium hexamethyldisilazide in 13 mL of THF at −80 °C was slowly added lactone **1** (0.96 g, 5 mmol, 1 equiv) in 2 mL of THF. The mixture was stirred for 0.5 h, and then a solution of dimethyl carbonate (4.21 mL, 4.5 g, 50 mmol, 10 equiv) in 3 mL of THF was slowly added. The solution was stirred for 12 h at −60 °C, and the mixture was allowed to warm to room temperature. The reaction was quenched by the addition of 20 mL of a saturated aqueous NH_4Cl solution and then extracted with ether. The organic layer was dried ($MgSO_4$) and evaporated. The yellow oil was flash chromatographed on silica gel eluting with a pentane−ether (85:15) eluant affording 1.16 g (4.65 mmol, 93%) of lactone as an inseparable diastereomeric yellow mixture (60:40): IR 3085, 1774, 1674, 1640, 1233 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 5.28 (m, 2H); 5.13 (m, 4H), 3.73 (s, 3H), 3.62 (m, 1H), 2.70 (m, 1H), 2.42 (m, 2H), 2.16 (m, 1H), 2.07−1.50 (m, 4H); ^{13}C NMR ($CDCl_3$) δ 171.4, 168.4 (s), 138.0 (d), 137.3 (d), 135.3 (d), 135.0 (d), 119.1 (t), 118.7 (t), 117.6 (t), 117.4 (t), 96.3 (s), 95.6 (s), 53.3 (d), 52.9 (q), 46.8 (d), 30.5 (t), 28.7 (t), 28.4 (t). Anal. Calcd for $C_{14}H_{18}O_4$: C, 67.18; H, 7.25. Found: C, 67.23; H, 7.30.

(3*S,6*S**,9*S**)-3-(Methoxycarbonyl)-3-methyl-6,9-divinyl-1-oxaspiro[4.4]nonan-2-one (5b).** To a stirred suspension of anhydrous powder K_2CO_3 (previously grinded and activated by heating at 50−60 °C under vacuum)(0.178 g, 1.3 mmol, 1.3 equiv) in 10 mL of anhydrous acetone were added under argon lactone **5a**, **6a** (0.25 g, 1 mmol, 1 equiv) and methyl iodide (0.213 g, 1.5 mmol, 1.5 equiv). After refluxing for 12 h, the mixture was cooled to room temperature and filtered. The cake was washed with acetone. The organic solution was concentrated and flash chromatographed on silica gel eluting with a petroleum ether−ether (90:10) affording 0.195 g (0.74 mmol, 74%) of lactone **5b** and 0.065 g of **6b** (0.24 mmol, 24%). **5b**: first eluted, white crystals, mp 45 °C; IR 1775, 1117 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 5.74 (ddd, J = 17.1, 10.2, 8.7 Hz, 1H), 5.56 (ddd, J = 16.9, 10.1, 9.5 Hz, 1H), 5.11 (m, 2H), 5.07 (m, 2H), 3.70 (s, 3H), 2.74 (br td, J = 8.7, 3.8 Hz, 1H), 2.59 ($^1/_2$AB, J = 13.80 Hz, 1H), 2.40 (br dt, J = 9.4, 9.0 Hz, 1H), 2.22 ($^1/_2$AB, J = 13.8 Hz, 1H), 2.24−2.15 (m, 1H), 1.92 (qd, J = 8.8, 4.4 Hz, 1H), 1.81−1.71 (m, 1H), 1.61−1.51 (m, 1H), 1.51 (s, 3H); ^{13}C NMR ($CDCl_3$) δ 175.1 (s), 171.5 (s), 138.2 (d), 135.4 (d), 118.4 (t), 117.5 (t), 94.6 (s), 53.6 (d), 52.9 (q), 52.4 (d), 51.4 (s), 37.3 (t), 28.5 (t), 28.2 (t), 22.0 (q). Anal. Calcd for $C_{15}H_{20}O_4$: C, 68.16; H, 7.63. Found: C, 68.12; H, 7.66. **6b**: oil, ^{1}H NMR ($CDCl_3$, 400 MHz) δ 5.68 (ddd, J = 17.1, 10.1, 9.1 Hz, 1H), 5.56 (ddd, J = 16.9, 10.1, 9.6 Hz, 1H), 5.18−4.99 (m, 4H), 3.74 (s, 3H), 2.83 (br td, J = 8.7, 2.6 Hz, 1H), 2.78 ($^1/_2$AB, J = 14.0 Hz, 1H), 2.33 (dt, J = 9.9, 9.2 Hz, 1H), 2.22 (dddd, J = 13.6, 10.9, 7.8, 4.8 Hz, 1H), 1.99−1.90 (m, 1H), 1.91 ($^1/_2$AB, J = 14.0 Hz, 1H), 1.82−1.72 (m, 1H), 1.63−1.55 (m, 1H), 1.45 (s, 3H); ^{13}C NMR ($CDCl_3$) δ 174.9 (s), 171.6 (s), 138.4 (d), 135.5 (d), 119.1 (t), 117.0 (t), 95.0 (s), 52.8 (q), 52.6 (d), 52.5 (d), 51.1 (s), 37.1 (t), 28.4 (t), 28.1 (t), 21.5 (q).

(3*R,6*S**,9*S**)-3-(Methoxycarbonyl)-3-(2-propyl)-6,9-divinyl-1-oxaspiro[4.4]nonan-2-one (5c).** Reaction of **5a**, **5b** and 2-iodopropane (0.255 g, 1.5 mmol, 1.5 equiv) gave **5c** (0.146 g, 0.5 mmol, 50% yield) and **6c** (0.047 g, 0.16 mmol, 12.5%). **5c**: IR 1772, 1734 cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 5.66−5.48 (m, 2H), 5.11−4.96 (m, 4H), 3.65 (s, 3H), 2.64 (m, 1H), 2.50 ($^1/_2$AB, J = 14.45 Hz, 1H), 2.40 (m, 1H), 2.25 ($^1/_2$AB, J = 14.45 Hz, 1H), 2.20−1.40 (m, 5H), 0.88 (d, J = 6.8 Hz, 3H), 0.80 (d, J = 6.8 Hz, 3H); ^{13}C NMR ($CDCl_3$) δ 173.0 (s) 170.0 (s), 137.5 (d), 134.9 (d), 117.9 (t), 117.2 (t), 93.0 (s), 60.2 (s), 53.2 (d), 52.7 (d), 52.5 (q), 34.3 (d), 31.0 (t), 28.2 (t), 27.9 (t), 17.8 (q), 17.5 (q). Anal. Calcd for $C_{17}H_{24}O_4$: C, 69.84; H, 8.27. Found: C, 69.72; H, 8.30. **6c**: ^{1}H NMR ($CDCl_3$, 200 MHz) δ 5.78−5.60 (m, 2H), 5.15−5.06 (m, 4H), 3.75 (s, 3H), 2.68 ($^1/_2$AB, J = 13.85 Hz, 1H), 2.62−2.38 (m, 2H), 2.05 ($^1/_2$AB, J = 13.85 Hz, 1H), 2.22−1.57 (m, 5H), 0.91 (d, J = 6.83, 3H), 0.85 (d, J = 6.83, 3H); ^{13}C NMR ($CDCl_3$) δ 173.1 (s), 170.4 (s), 138.1 (d), 136.2 (t), 118.9 (t), 116.9 (t), 94.8 (s), 60.5 (s), 52.9 (q), 52.0 (d), 51.5 (d), 33.1 (d), 28.7 (t), 27.8 (t), 27.6 (t), 18.2 (q), 17.9 (q).

Computational Methods. Computer modeling was carried out with the Hyperchem program (version 4.5) from Hypercube, Inc. on a PC equipped with a 200 MHz Pentium-Pro. Structures were minimized with the following parameters: AM1, PM3, or *ab initio* STO-3G basic set; restricted Hartree−Fock (RHF) level; minimization algorithm, until the rms energy gradient was less than 0.001 (PM3), 0.005 (STO-3G) kcal/mol Å; accelerated convergence. Calculations concerning **7** were carried out with the Gaussian 94 on an IDRIS workstation.

Acknowledgment. The authors thank Dr. I. D. R. Stevens (The University of Southampton, U.K.) for reading the manuscript and for valuable comments and Dr. M. Rajzmann for his valuable assistance on *ab initio* calculations. We are indebted to Dr. R. Faure for his assistance in NMR measurements.

Supporting Information Available: ^{13}C NMR spectra (14 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

JO962302I