$(CH_2)_2CO_2Et$, 131379-29-8; (*E*)-$CH_3CH{=}CHCH_2C_6H_4$-*p*-CO_2Et, 131379-30-1; $H_2C{=}CHCH(Ph)CH_2(CH_2)_5CN$, 131379-31-2; (*E*)-$CH_3CH{=}CH(CH_2)_4CO_2Et$, 61141-97-7; $H_2C{=}CHC(CH_3)(CH_3)CH_2(CH_2)_2CO_2Et$, 109976-59-2; $H_2C{=}CHC(CH_3)(CH_3)CH_2(CH_2)_5CN$, 131379-32-3; $H_2C{=}CHC(CH_3)(CH_3)CH_2CH_2Pgh$, 61142-18-5; *p*-$COCH_3C_6H_4(CH_2)_3CO_2Et$, 71665-59-3; *p*-$CNC_6H_4(CH_2)_3CO_2Et$, 131379-33-4; *p*-$NO_2C_6H_4(CH_2)_3CO_2Et$, 34153-33-8; *p*-$CNC_6H_4C_6H_4$-*p*-$CO_2Et$, 89409-89-2; *p*-$CO_2EtC_6H_4C_6H_4$-*p*-$CO_2Et$, 47230-38-6; *m*-$CO_2EtC_6H_4C_6H_4$-*p*-CN, 131379-34-5; *p*-$CNC_6H_4C_6H_4$-*p*-CN, 1591-30-6; *o*-$CNC_6H_4C_6H_4$-*m*-CO_2Et, 131379-35-6; $PhC(=CH_2)CH=CH_2$, 2288-18-8; $PhC(=CH_2)C(CH_3)=CH_2$, 18476-73-8; $H_2C{=}CHCH{=}CHC_6H_4$-*o*-CO_2Et, 131379-36-7; $H_2C{=}C(CH_3)CH{=}CHC_6H_4$-*o*-$CO_2Et$, 131379-37-8; *m*-$BrZnC_6HCO_2Et$, 131379-38-9; bromo[3-(ethoxycarbonyl)propyl-*C*,*O*]zinc, 131379-39-0; bromo[2-(ethoxycarbonyl)phenyl-*C*,*O*]zinc, 131379-40-3; chloro[3-(ethoxycarbonyl)propyl]-*C*,*O*]zinc, 131379-41-4; cyclohexyl bromide, 108-85-0; 3-cyclohexylcyclohexanone, 7122-93-2; 3-(4-carbethoxyphenyl)cyclohexanone, 131379-22-1; lithium 2-thienylcyanocuprate, 112426-02-5.

Supplementary Material Available: ^1H and ^{13}C NMR spectra and spectral data for the new title compounds (32 pages). Ordering information is given on any current masthead page.

The Generation and Rearrangement of 2-(Diazoacetyl)cyclobutanones: The Formation of 5-Spirocyclopropyl-2(5*H*)-furanones

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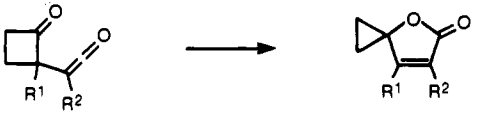
We describe here a simple synthesis of 2-(diazoacetyl)cyclobutanones and their facile thermal rearrangement to 5-spirocyclopropyl-$\Delta^{\alpha,\beta}$-butenolides. The yield of the rearrangement product is high, and the reaction is completely stereospecific. α-Ketenylcyclobutanones have been identified spectroscopically as intermediates, and their rearrangement was studied kinetically. A strained dipolar cyclic transition is proposed for the rearrangement of the α-ketenylcyclobutanones to the corresponding 5-spirocyclopropyl-$\Delta^{\alpha,\beta}$-butenolides.

Introduction

Strained ring compounds, long of interest to the organic chemist because of their curious chemical and spectroscopic properties,[1] have recently attracted the interest of the synthetic organic chemist due to the explosive development of synthetic routes to highly functionalized starting materials.[2] For no class of materials has this interest been more apparent than for the cyclobutanones[2e,f,3] where a virtual plethora of new synthetic routes have stimulated their use as synthetic intermediates. These materials also show, in addition to a vast variety of strain-driven ground-state reactions and rearrangements, a rich and varied photochemistry.[3,4]

We have been interested for some time in rearrangements of cyclobutanone derivatives.[5] This began with the discovery that a number of cyclobutanones underwent a variety of electrophilically initiated ring opening reactions in the presence of appropriate electrophile–nucleophile combinations. Our initial studies first utilized Lewis acid catalysts in the presence of compatible nucleophiles[5b,c] and evolved to reagents containing both reactants in a single molecule (e.g., trimethylsilyl iodide).[5d] In each case, regioselective ring opening of the cyclobutanone ring was observed with the formation of polyfunctionalized products. We were interested in determining whether appropriately masked electrophilic functionality tethered to a cyclobutanone ring could be selectively activated in the presence of the highly strained carbonyl functionality and utilized to initiate interesting intramolecular electrophilic rearrangements. In this regard, the electrophile after initiating the structural rearrangement should ideally be transformed into a nucleophilic reagent capable of terminating the reaction intramolecularly. In many cases, functional groups such as ketenes and isocyanates can play such a dual role.[6] It was envisioned that such reactants bonded appropriately to the α-position of a cyclobutanone derivative might promote the rearrangement shown below to generate a variety of interesting 5-spirocyclopropylbutenolides.



(1)

$\Delta^{\alpha,\beta}$-Butenolides are valuable synthetic reagents which constitute the active functionality of many known natural products, and many synthetic approaches to these materials have been developed and described.[7] Similarly, many

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(3) Bellus, D.; Ernst, B. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 797.

(4) Morton, D. R.; Turro, N. J. *Adv. Photochem.* **1974**, *9*, 197.

(5) (a) Miller, R. D.; Abraitys, V. *J. Am. Chem. Soc.* **1972**, *94*, 668. (b) Miller, R. D.; McKean, D. R. *Tetrahedron Lett.* **1979**, 583. (c) Miller, R. D.; McKean, D. R. *Ibid.* **1979**, 1003. (d) Miller, R. D.; McKean, D. R. *Ibid.* **1980**, *21*, 2639.

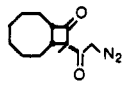
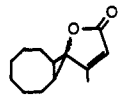
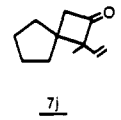
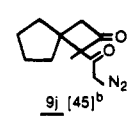
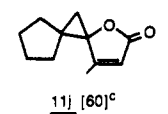
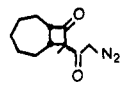
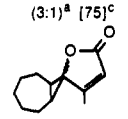
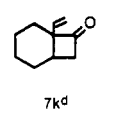
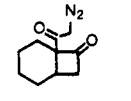
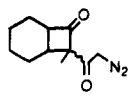
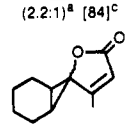
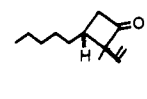
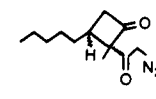
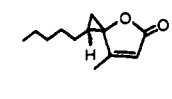
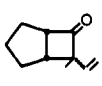
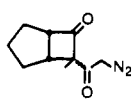
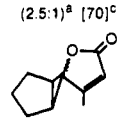
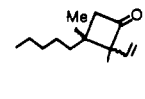
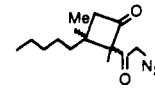
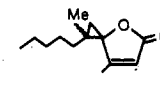
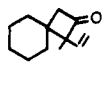
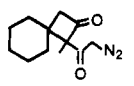
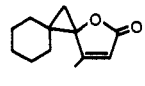
(6) (a) Ulrich, H. In *Cycloaddition Reactions of Heterocumulenes*; Blomquist, A. T., Ed.; Academic Press: New York, 1967. (b) *The Chemistry of Functional Groups: The Chemistry of Ketenes, Allenes, and Related Compounds*; Patai, S., Ed.; John Wiley and Sons: New York, 1980; Parts I and II.

(7) For a comprehensive review of butenolide derivatives, see: Rao, Y. S. *Chem. Rev.* **1976**, *76*, 625.

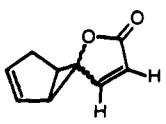
(8) (a) Breslow, R.; Altman, L. J.; Krebs, A.; Eohacsi, E.; Murata, I.; Peterson, R. A.; Posner, J. *J. Am. Chem. Soc.* **1965**, *87*, 1326. (b) Breslow, R.; Altman, L. J. *Ibid.* **1966**, *88*, 564. (c) Breslow, R.; Oda, M.; Pecoraro, J. *Tetrahedron Lett.* **1972**, 4415. (d) Dehmlow, S. S.; Dehmlow, E. V. *Z. Naturforsch.* **1975**, *306*, 404.

0022-3263/91/1956-1453$02.50/0

Table I. Preparation and Thermal Rearrangement of 2-(Diazoacetyl)cyclobutanones According to Scheme II

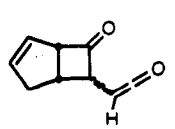
entry	starting material	products		entry	starting material	products	
1.	 7a,b (3:1)[a]	 9a,b (3:1)[a] [50][b]	 11a,b (3:1)[a] [75][c]	6.	 7j	 9j [45][b]	 11j [60][c]
2.	 7c,d (3:1)[a]	 9c,d (2.5:1)[a] [65][b]	 11c,d (2.2:1)[a] [84][c]	7.	 7k[d]	 9k [40][b]	 11k [55][c]
3.	 7e,f (2:1)[a]	 9e,f (2.5:1)[a] [65][b]	 11e,f (2.5:1)[a] [70][c]	8.	 7l,m (7:3)[a]	 9l,m (1:1)[a] [45][b]	 11l,m (1:1)[a] [73][c]
4.	 7g,h (7:3)[a]	 9g,h (1.9:1)[a] [45][b]	 11g,h (1.9:1)[a] [66][c]	9.	 7n,o (1:1)[a]	 9n,o (1:1)[a] [45][b]	 11n,o (1:1)[a] [77][c]
5.	 7i	 9i [66][b]	 11i [60][c]				

routes to the conjugation-extended 5-alkylidene and arylidene derivatives have also been reported. It is surprising therefore that 5-spirocyclopropyl-$\Delta^{\alpha,\beta}$-butanolides are virtually unknown, in spite of the fact that they represent a homoconjugated variation of the 5-alkylidene derivates and as such might be expected to have interesting properties and possible synthetic potential. A few structurally related 5-spirocyclopropenyl derivatives have been reported from the thermal and transition metal catalyzed dimerization of a number of substituted cyclopropenones, and some 5-spirocyclopropyl-2,3-benzobutenolides have been isolated from the in situ trapping by olefins of the oxacarbene produced upon irradiation of 1,2-benzocyclobutenedione.[9] In addition, we have reported the isolation of a pair of epimeric 5-spirocyclopropylbutenolides **1** from the pyrolysis of the strained polycyclic diketone.[10] Evidence derived from trapping experiments suggested that the α-ketenyl cyclobutanone derivative **3** was an intermediate in the pyrolysis of **2**.



1

2



3

This preliminary work suggested the viability of a rearrangement such as shown in eq 1, provided a facile synthetic route to a variety of α-ketenylcyclobutanones could be uncovered. Our goals, therefore, were to (i) develop a synthetic procedure for the generation of α-ketenylcyclobutanones, (ii) to determine the generality of the rearrangement to produce 5-spirocyclopropyl $\Delta^{\alpha,\beta}$-butenolides, (iii) to study the mechanism of the rearrangement, and (iv) to examine the stereoselectivity, if any, present in the reaction. We now report the development of a synthetic route to a variety of substituted α-ketenylcyclobutanones from the pyrolysis or photolysis of the corresponding 2-diazocarbonylcyclobutanone derivatives and discuss their facile rearrangement to produce 5-spirocyclopropyl-$\Delta^{\alpha,\beta}$-butenolides.

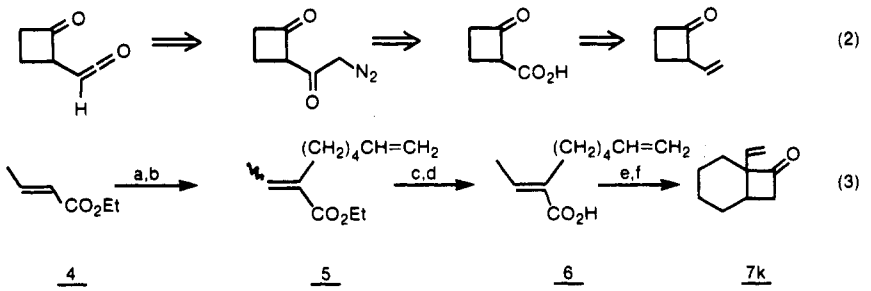
Results and Discussion

Retrosynthetic analysis on α-ketenyl-substituted cyclobutanone derivatives suggests that 2-vinylcyclobutanones should be reasonable precursors (see Scheme I). These latter materials, which are themselves valuable synthetic precursors to substituted cyclopentenones and cyclohexenones, have been extensively studied[11] and a number of useful synthetic routes have been developed. Among these, the inter-[11a,h,g,12] and intramolecular[13] cycloaddition

(9) Staab, H. A.; Ipaktschi, J. *Chem. Ber.* **1968**, *101*, 1457.
(10) Miller, R. D.; Dolce, D. L. *Tetrahedron Lett.* **1975**, 1831.

(11) (a) Matz, J. R.; Cohen, T. *Tetrahedron Lett.* **1981**, *22*, 2459. (b) Cohen, T.; Matz, J. R. *Ibid.* **1981**, *22*, 2455. (c) Jackson, D. A.; Rey, M.; Dreiding, A. S. *Ibid.* **1983**, *24*, 4817. (d) Huston, R.; Rey, M.; Dreiding, A. S. *Helv. Chem. Acta* **1982**, *65*, 451. (e) Cohen, T.; Bhupathy, M.; Matz, J. R. *J. Am. Chem. Soc.* **1983**, *105*, 520. (f) Bhupathy, M.; Cohen, T. *Ibid.* **1983**, *105*, 6978. (g) Danheiser, R. L.; Martinez-Davila, C.; Sard, H. *Tetrahedron* **1981**, *37*, 3943. (h) Danheiser, R. L.; Gee, S. K.; Sard, H. *J. Am. Chem. Soc.* **1982**, *104*, 7670. (i) Gadwood, R. C.; Lett, R. M. *J. Org. Chem.* **1982**, *47*, 2268. (j) Gadwood, R. C.; Lett, R.; Wessinger, J. E. *J. Am. Chem. Soc.* **1984**, *106*, 3869. (k) Gadwood, R. C.; Lett, R.; Wissinger, J. E. *Ibid.* **1986**, *108*, 6343.
(12) (a) Huston, R.; Rey, M.; Dreiding, A. S. *Helv. Chem. Acta* **1982**, *65*, 1563. (b) Trahanovsky, W. S.; Surber, B. D.; Wilkes, M. C.; Preckel, M. M. *J. Am. Chem. Soc.* **1982**, *104*, 6779. (d) Rey, M.; Dunkelblum, E.; Allain, R.; Dreiding, A. S. *Helv. Chem. Acta* **1970**, *53*, 2159. (e) Berge, J.; Rey, M.; Dreiding, A. S. *Ibid.* **1982**, *65*, 2230. (f) Payne, G. B. *J. Org. Chem.* **1966**, *31*, 718. (g) Jackson, D. A.; Rey, M.; Dreiding, A. S. *Helv. Chem. Acta* **1983**, *66*, 2330. (h) Rey, M.; Roberts, S.; Diffenbacher, A.; Dreiding, A. S. *Ibid.* **1970**, *53*, 417. (i) Rey, M.; Dunkelblum, E.; Allain, R.; Dreiding, A. S. *Ibid.* **1970**, *53*, 2159.

Scheme I[a]



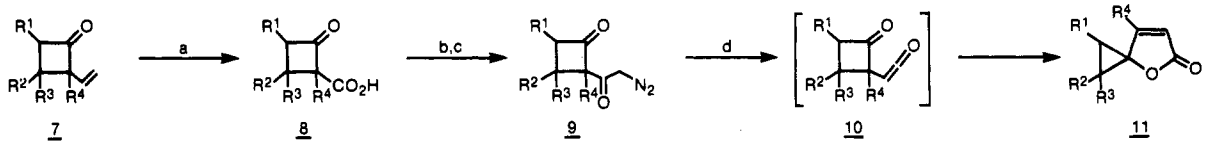
(2)

(3)

4 5 6 7k

[a] (a) LDA, THF–HMPTA, –78 °C; (b) $Br(CH_2)_4CH{=}CH_2$, –78 °C, 1 h, 0 °C, 1.5 h; (c) KOH–EtOH, reflux, 1 h; (d) 6 N HCl; (e) $(COCl)_2$; (f) triethylamine–cyclohexane, 150 °C, 4 days.

Scheme II[a]



(4)

7 8 9 10 11

[a] (a) $RuCl_3{\cdot}H_2O$, $NaIO_4$, CH_3CN–H_2O/CCl_4, 25 °C, 4 h; (b) $(COCl)_2$, 25 °C; (c) CH_2N_2, Et_2O, –10 °C; (d) Δ, xylene, 30 min.

of vinyl ketene derivatives to substituted olefins and dienes is particularly convenient. The intermolecular procedure has been extensively investigated by Dreiding and coworkers who have described the preparation of a large number of mono- and fused-ring 2-vinylcyclobutanones.[12g]

We have successfully employed this procedure, which involves the in situ generation of the desired vinyl ketenes by the high temperature dehydrohalogenation of appropriately substituted unsaturated acid chlorides in the presence of olefinic trapping reagents, to prepare the vinyl cyclobutanones shown in Table I. With the exception of **7k**, all of the vinyl cyclobutanones in Table I were prepared by the cycloaddition of the vinyl ketene produced in situ from the acid chloride of tiglic acid with the appropriate olefin. As previously described by Dreiding, the materials produced from monosubstituted, cyclic or unsymmetrically 1,2-disubstituted olefins are generated as very difficultly, separable epimeric mixtures. For the cycloadducts formed from simple cyclic olefins, these authors have shown by detailed ^1H NMR studies that the major isomer is always the one where the alkyl substituent of the original vinyl ketene appears in the endo position of the bicyclic product,[12g,h] a stereochemistry consistent with the steric requirements of the proposed orthogonal $\pi 2s + \pi 2a$ transition state for ketene cycloadditions. It has also been noted empirically that a syn stereochemical relationship of a methyl substituent in position 2 of the cyclobutanone ring relative to the other carbon substituents in positions 3 and 4 results in significant upfield shift of the methyl signal in the ^1H NMR spectrum relative to the comparable signal for the epimer ($\Delta\delta$ = 0.1–0.3). Similar and complementary shifts are observed for the H-C(1′) olefinic proton of the vinyl group as a function of configuration. On this basis, we have assumed that the methyl substituent of the major vinyl cyclobutanone isomers in examples **7a–h** and presumably also **7l,m** is in the endo position for the bicyclic derivatives and is syn to the pentyl substituent in example **7l**. This was further confirmed by an X-ray structural analysis of the separated major diazo ketone isomer **9e** produced by subsequent chemical transformation of the epimeric mixture **7e,f** (vide infra). This assumes, of course, that the subsequent conversion of the respective olefins into the diazo ketones **9e** and **9f** proceeds without change in configuration at the α-carbon, an assumption which appears quite reasonable. The preparation of **7k** was accomplished by an intramolecular variant of the vinylketene cycloaddition as shown in (Scheme I, eq 3). This cycloaddition, which according to the nomenclature proposed by Snider,[13] is a type I variant based on the position or attachment of the ketene functionality, works well, but requires elevated reaction temperatures and extended reaction times. Although, numerous examples of intramolecular vinylketene cycloadditions to produce 1-vinylbicyclo[3.2.0]heptan-7-ones have been reported,[13] this seems to be the first report of the preparation of a 1-vinylbicyclo[4.2.0]octan-8-one derivative by this route, and as such represents an extension of this valuable methodology.

The subsequent transformation of the vinylcyclobutanones to the diazo ketones is described (Scheme II, eq 4), and the results are reported in Table I. Although oxidative ozonolysis is often used to convert monosubstituted olefins to carboxylic acids,[14] this approach was rejected because of potential complications caused by the facile Baeyer–Villiger type rearrangement of cyclobutanone derivatives. On the other hand, such problems were not anticipated for heavy metal oxidants such as ruthenium tetraoxide.[15] Recently, Sharpless et al.[16] have described a greatly improved catalytic procedure which employs acetonitrile as a complexing cosolvent. The application of this technique for the oxidation of the vinyl cyclobutanones shown in Table I generated the desired carboxylic acids in yields varying from 65 to 90%. For the oxidation, ruthenium trichloride trihydrate was employed at a level of 4.5 mol %. As expected, the β-keto acids [IR 3500–2400 cm^{-1} (–OH), 1780 cm^{-1} (C=O, cyclobutanone), 1700–1710 cm^{-1} (C=O, carboxylic acid)] are somewhat

(13) The intramolecular cycloaddition of vinyl ketene derivatives has been extensively studied. For a comprehensive recent review of this topic see: Snider, B. B. *Chem. Rev.* **1988**, *88*, 793.

(14) Bailey, P. S. In *Ozonations in Organic Chemistry*; Trahanovsky, W. S., Ed.; Academic Press: New York, 1978.

(15) Lee, D. G.; van den Engh, M. In *Oxidation in Organic Chemistry*; Trahanovsky, W. S., Ed.; Academic Press: New York, 1973; Part B, Chapter 4.

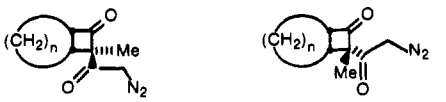
(16) Carlsen, P. H. J.; Katsuki, T.; Martin, V. S.; Sharpless, K. B. *J. Org. Chem.* **1981**, *46*, 3937.

unstable[17] and were purified only by basic extraction. Materials isolated in this manner were converted directly to the acid chlorides [IR 1780–1800 cm^{-1}, 1760–1770 cm^{-1} (sh)] by treatment with neat oxalyl chloride (5 mmol of acid/2 mL of oxalyl chloride) at room temperature for 10–15 h. The excess oxalyl chloride was removed under vacuum, and the crude acid chlorides were flash distilled in a Kugelrohr apparatus at high vacuum ($<10^{-3}$ Torr). The crude acid chlorides were also not particularly stable and colorized rapidly upon standing. For this reason, they also were used without further purification and were converted directly to the diazo ketones **9a–o** shown in Table I.

The diazo ketones prepared as described were relatively stable and could be purified by flash column chromatography.[18] Products produced from stereoisomeric mixtures of the starting vinylcyclobutanones were initially isolated also as epimeric mixtures. Subsequent separation of the epimeric diazo ketones could usually be accomplished by subsequent careful flash column chromatography. The diazo ketones were all characterized by intense IR absorptions around 2110 cm^{-1} (diazo), 1640 and 1350 cm^{-1} (diazo ketone), and 1765–1775 cm^{-1} (cyclobutanone carbonyl). The methine proton of the diazocarbonyl group appeared as a singlet from δ 5.3–5.7 in the ^1H NMR spectra and these signals could conveniently be used to determine the epimeric composition. The diazo ketones also showed characteristic ^{13}C resonances around 210 and 190 ppm for the carbonyl groups of the cyclobutanone and the diazo carbonyl, respectively, and the carbon atom of the diazo group routinely appeared around 50 ppm relative to TMS.

Pyrolysis. The 2-(diazoacetyl)cyclobutanones **9a–o** were thermally labile and rearranged upon brief heating in refluxing xylene. The characteristic diazo absorption in the infrared around 2110 cm^{-1} disappeared completely within 30 min and the rearrangement products were isolated in a high state of purity simply by removing the solvent. The only volatile products from the thermal rearrangement were the 5-spirocyclopropyl $\Delta^{\alpha,\beta}$-butenolides shown in Table I. The unusual structure of these products was confirmed by spectral analyses. In addition, the structure of the major isomer generated by the pyrolysis of the epimeric diazo ketone mixture **9e,f** was confirmed by single-crystal X-ray analysis (vide infra). In most cases, the epimeric lactones could be separated by repeated flash column chromatography. The spectral data of these products are consistent with the structural assignments. In the infrared, a characteristic high frequency carbonyl absorption appeared around 1750–1760 cm^{-1} when recorded in nonpolar solvents. In chloroform, this band shifts to lower frequencies (1730–1745 cm^{-1}). The ^1H NMR spectra of the butenolide products showed a single vinyl proton between δ 5.7 and 5.9 with weak coupling (J = 1–2 Hz) to the allylic methyl group. The ^{13}C spectra are characteristic, with the quaternary carbonyl carbon falling between 171 and 174 ppm. Each vinyl carbon was easily distinguished, since the β-carbon of the α,β-butenolide segment appears considerably downfield (167–173 ppm) from the corresponding α-carbon (114–119 ppm) due to electronic effects. All of the lactones show parent ions by electron impact mass spectrometry and absorbed strongly in the UV: I_{max}^{MeOH} 235–245 nm; ϵ = 10 000–20 000.

Stereochemistry of the Rearrangement. Interestingly, the rearrangement of the diazo ketones to the 5-spirocyclopropyl-$\Delta^{\alpha,\beta}$-butenolides appears to be stereospecific. This was first indicated by the observation that rearrangement of diazo ketone isomer mixtures gave epimeric lactone mixtures in approximately the same ratios. The isomer ratios of both starting materials and products could conveniently be determined by ^1H NMR spectroscopy. The suggestion that the rearrangement was stereospecific was subsequently confirmed by thermal studies on separated epimers. In this regard, the diazo ketones **9e** and **9f** and **9g** and **9h**, which were separated by column chromatography, were studied in some detail. On the basis of its ^1H NMR spectrum, the stereochemistry of the major isomer is tenatively assigned as structure **9e**. This assignment was also consistent with the observation that it was produced from the major vinylcyclobutanone epimer **7e** which had previously been assigned as the 7-*endo*-methyl isomer isomer on the basis of ^1H NMR analysis. The methyl resonance in **9e** is considerably upfield from that in **9f** (1.26 vs 1.54 ppm) which is also consistent with the 7-*endo*-methyl configuration. There are other significant differences in the ^1H NMR spectra of **9e** and **9f**, but they are less convincingly correlated with the epimeric configuration. For example, the methine hydrogen of the diazo group in **9e** appears upfield by almost 0.5 ppm relative to the comparable resonance in **9f** (5.4 vs 5.9 ppm). There are also large differences in the separation between the resonances assigned to the cyclobutanone methine protons on carbons 1 and 6 ($\Delta\delta$ = 0.31 for **9e** versus $\Delta\delta$ = 1.1 for **9f**). This may reflect the increased shielding of the proton at C-6 by the syn diazocarbonyl functionality. Exactly the same trends and patterns were observed in the ^1H NMR spectra of the separated isomers **9g** and **9h** which also leads to the assignment of the major isomer **9g** as the 6-*endo*-methyl derivative. The tentative stereochemical assignment for **9e** was subsequently confirmed by single-crystal X-ray analysis on crystals grown from hexane.



9e (n=4) **9g** (n=3) **9f** (n=4) **9h** (n=3)

With the structural assignments secured for the epimeric pairs **9e,f** and **9g,h**, the thermolysis of each individual sample was investigated. In each case, the purified isomer produced a single lactone with no evidence of crossover for either epimeric pair. For these and other purified samples, it appears that the thermal rearrangement is completely stereospecific.

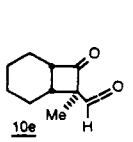
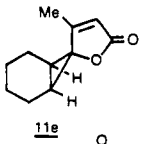
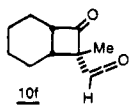
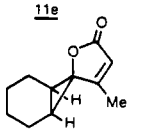
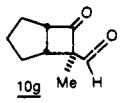
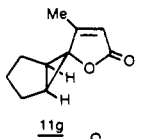
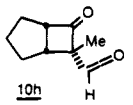
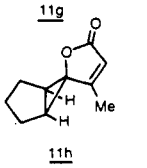
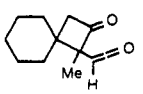
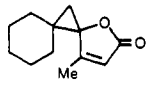
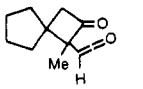
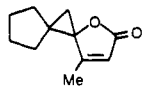
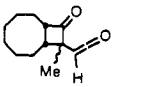
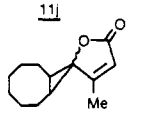
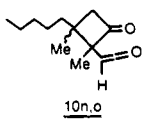
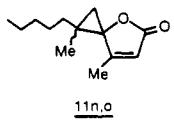
With the stereospecificity of the rearrangement confirmed, it remained to determine the actual stereochemistry of the lactone products. Here, because of the large structural changes, the ^1H NMR spectra were not so easily interpreted in terms of the product stereochemistry. Fortunately, the lactone produced from **9e** was crystalline and single-crystal X-ray analysis confirmed structure **11e**. On the basis of this information, coupled with the close strong similarity of the basic proton NMR spectral features in the series **9e,f** and **9g,h** and **11e,f** and **11g,h**, the structure of the lactone produced from the major diazo ketone isomer **9g** was assigned as **11g**.

The stereochemical consequences of the rearrangement can be summarized as follows. The thermal rearrangement appears to be completely stereospecific with no detectible crossover. This was true in every case where the pure diazo

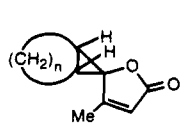
(17) Reports of 2-carboxycyclobutanones in the recent literature are relatively rare. To our knowledge, only the parent and a few specific derivatives have been described: (a) Amice, P.; Conia, J. M. *Bull. Chim. Soc. Fr.* **1974**, 1015. (b) Amice, P.; Conia, J. M. *Tetrahedron Lett.* **1974**, 479. (c) Ashkanagi, P.; Kalo, J.; Ruttman, A.; Ginsberg, D. *Tetrahedron* **1978**, *34*, 216. (d) Zimmerman, H. E.; Solomon, R. D. *J. Am. Chem. Soc.* **1986**, *108*, 6276.

(18) Still, W. C.; Kahn, M.; Mitra, A. *J. Org. Chem.* **1978**, *43*, 2923.

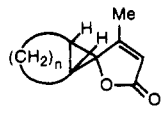
Table II. Kinetics of Rearrangement of 2-Ketenylcyclobutanones

entry	ketene[a]	lactone	$k^{-5}(\times 10^5)$, s^{-1}	k_{rel}
1.	 10e	 11e	0.15	1
2.	 10f	 11f	21.7[b]	—
3.	 10g	 11g	0.61	4
4.	 10h	 11h	5.7	24
5.	 10i	 11i	8.2	53
6.	 10j	 11j	65.6	428
7.	 10a,b (7.5:1)	 11a,b (6:1)	0.98	6
8.	 10n,o	 11n,o	20.0	133

ketone isomers were separated and studied. Assuming that the corresponding ketene is an intermediate in the pyrolysis and that the Wolff rearrangement of the diazo ketones to the corresponding ketenes maintains the same relative configuration at the α-carbon atom of the cyclobutanone,[19] the stereochemical results suggest that the ring oxygen of the lactone product appears with the same stereochemical configuration relative to the bridgehead methine hydrogens (i.e., either syn or anti) as in the original diazocarbonyl moiety of the starting diazo ketone.

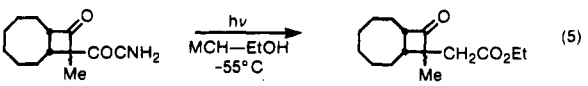


11e (n=4)
11g (n=3)



11f (n=4)
11h (n=3)

Although α-ketenylcyclobutanones such as **10** (see Scheme II) are reasonable intermediates to be expected from the pyrolysis of the diazo ketones, the vigorous thermal conditions preclude the spectroscopic identification of the intermediates due to their kinetic instability. However, irradiation of the diazo ketones (λ > 330 nm) in the presence of alcohols proceeds to the expected keto esters in a stereospecific fashion. This was first suggested by the observation that epimeric diazo ketone mixtures upon irradiation yielded epimeric keto esters in very similar ratios to the starting materials. For example, the diazo ketone mixture **9a,b**, for which the epimeric ratio was determined to be 7.3:1 by ^{1}H NMR, produces an epimeric mixture of keto esters in almost the same ratio (6:1) upon irradiation. The major isomer of **9a,b** is the *endo*-methyl derivative on the basis of the upfield ^{1}H NMR shift observed for the methyl group in the major diazo ketone epimer relative to the minor epimer (1.2 vs 1.5 ppm). Similarly, it was reasonably assumed that the photochemical Wolff rearrangement proceeds with configurational retention of the migrating group in the production of the keto esters **12a,b**. Consistant with this proposal is the observation that the α-methyl proton signal for the major keto ester isomer **12a** also appears upfield relative to those in the minor isomer (1.07 vs 1.41 ppm).



(5)

9a,b (7.3:1) 12a,b (6.0:1)

The stereospecifity of the photochemical Wolff rearrangement was further confirmed by irradiation of the separated epimers **9e**, **9f**, **9g**, and **9h** each at low temperatures in a 6:1 mixture of methylcyclohexane–ethanol. In each case, a single epimeric keto ester **12e**, **12f**, **12g**, and **12h**, respectively, was produced. The stereochemical assignment of the keto esters is tentative and is based primarily on ^{1}H NMR chemical shift analyses, as described earlier. The behavior of the diazo ketone epimer **9f** is somewhat unusual, since the low-temperature irradiation concurrently produced small amounts of the lactone **11f** in addition to the keto ester **14f** (ratio 1:3.4), suggesting that the unimolecular ketene–lactone rearrangement is competitive even at low temperatures for this epimer. The α-ketenylcyclobutanone intermediates themselves can be detected spectroscopically when the irradiation is conducted at low temperatures in nonpolar solvents. For example, when the diazo ketones were dissolved in methylcyclohexane (MCH) and irradiated (λ > 330 nm) between −40 and −50 °C, the disappearance of the diazocarbonyl bands around 2110 and 1640 cm^{-1} in the infrared was accompanied by the appearance of a strong ketene absorption at 2120 cm^{-1}. Generally, the low-temperature irradiation allows the transformation of the starting diazo ketone under conditions where the keto ketene products are relatively stable (an exception would be isomer **10f**). Subsequent warming to room temperature results in the disappearance of the α-ketenylcyclobutanone absorptions (2120 and 1770 cm^{-1}) and the appearance of bands due to the corresponding spirocyclopropyl $\Delta^{\alpha,\beta}$-butenolides. Kinetic plots [ln ($A - A_0$) vs time] for the disappearance of the ketene band in the IR yield the respective rate constants which are reported in Table II. The kinetics were first-order in ketene, and the plots were linear over at least 4 half-lives. The spiro-$\Delta^{\alpha,\beta}$-butenolides were the only isolable products produced upon warmup of the irradiated solutions. In these cases, as described previously for the

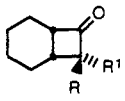
(19) Meier, H.; Zeller, K.-P. *Angew. Chem., Int. Ed. Engl.* **1975**, *14*, 32.

Table III. Solvent Studies on the Thermal Rearrangement of the Ketene Derived from 9e

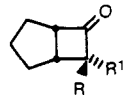
solvent	k^{30} (×10^5)	relative rate	$\Delta H^{\ddagger}$, kcal/mol	$\Delta S^{\ddagger}$, eu
methylcyclohexane	2.8	1.0	12.4	-38.6
toluene	10.7	3.8	14.0	-29.6
chloroform	85[b]	30	12.5	-31.3

[a] Initial concentration, 5 × 10^{-3} M. [b] Rate constant at 30 °C extrapolated from measurements at lower temperatures.

thermal decomposition of the diazo ketones, the rearrangement is also completely stereospecific.



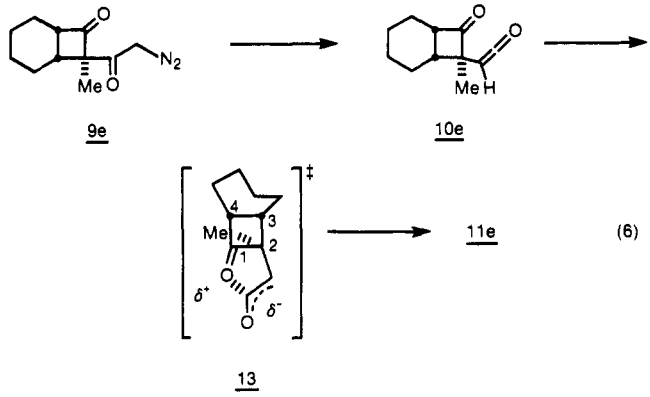
12e R=CH_2CO_2Et, R^1=Me
12f R=Me, R^1=CH_2CO_2Et



12g R=CH_2CO_2Et, R^1=Me
12h R=Me, R^1=CH_2CO_2Et

The rate of rearrangement is quite structure sensitive, and differences in the first-order rate constants of more than 2 orders of magnitude were observed for the ketenes studied here. Some of the kinetic data reported in Table II were derived from the study of epimeric mixtures (entries **10a,b** and **10n,o**). This procedure causes no difficulties as long as the rate of rearrangement of each epimer is comparable. While this is certainly the case for the monocyclic derivatives (e.g., we have independently measured the rates of rearrangement of each purified epimer **10n** and **10o** in MCH and find that the individual rate constants are within 15% of one another), it is not always true, particularly in the bicyclic cases where the epimeric rates may be very different. For example, while the ketene **10f** produced from the diazo ketone **9f** is unusually unstable and its disappearance must be monitored at very low temperatures (<−30 °C) in a cryostat, the rearrangement of the epimer **10e** can conveniently be studied from 20 to 60 °C. Large differences in the rates of rearrangement of epimers sometimes causes kinetic difficulties manifested by nonlinear rate plots when mixtures are studied kinetically.

The solvent dependence of the α-ketenylcyclobutanone–spirocyclopropyl-$\Delta^{\alpha,\beta}$-butenolide rearrangement was studied for the ketene **10e** derived from the diazo ketone **9e**. This material was selected because the diazo ketone epimers are easily separated by flash column chromatography and the ketene **10e** rearranges over a temperature range which is convenient for measurement. The range of useful solvents is very much restricted both by the mode of generation of the ketene and the reactivity of the intermediate. Table III shows that the rearrangement of **10e** is considerably faster in a more polar solvent such as chloroform than in methylcyclohexane. Surprisingly, the activation enthalpy is relatively uneffected by the change in solvent polarity. The entropy of activation, however, is very negative and is solvent dependent. Large negative entropies of activation seem to be a characteristic of the rearrangement in general and were observed for a number of α-ketenylcyclobutanones, although the absolute values of $\Delta S^{\ddagger}$ were quite structure dependent. The large negative values for the entropies of activation are consistant with a highly ordered cyclic transition state.[20] It appears also that there is an appreciable electrostatic component to the entropy of activation which is evidenced by the significant solvent dependence. The observed decreasingly negative value for $\Delta S^{\ddagger}$ with increasing solvent polarity is also consistent with a highly polar transition state.[20] The significant solvent effects on the rearrangement of **10e** and **11e** coupled with the highly negative values for the activation entropies leads us to postulate a cyclic polar transition state such as **13**. From **13**, the observed product **11e** can be produced stereospecifically by the migration of the 2,3-bond to the carbonyl carbon atom 1 from the same relative face of the cyclobutanone ring as originally occupied by the ketene moiety.



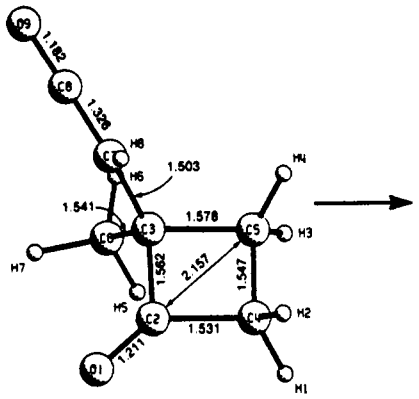
9e 10e 11e (6)

13

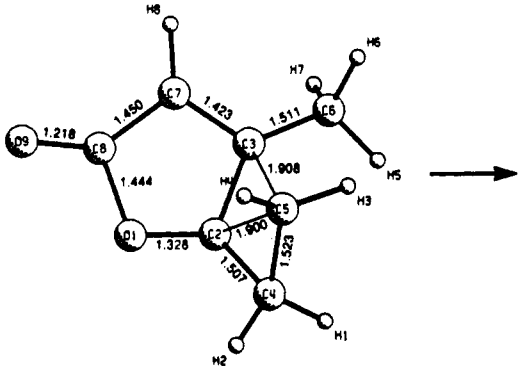
This transition-state model also suggests a possible explanation for the large rate differences observed for certain epimeric ketene pairs such as **10e** and **10f** and **10g** and **10h**. In the proposed transition state **13** produced from **10e** by bonding between the cyclobutanone oxygen and the ketene carbonyl carbon, the three alkyl substituents at C_2, C_3, and C_4 all interact on the same side of the cyclobutane ring creating considerable steric congestion. This steric hinderance is further exacerbated if significant twisting occurs during the interaction of the ketene moiety with the cyclobutanone carbonyl group. On the other hand, with the epimer **10f**, the methyl substituent at C_2 is on the opposite side of the ring and does not interact significantly with the carbon atoms of the tetramethylene bridge in the transition state, hence, the rate of rearrangement is apparently accelerated.

The rearrangement of a model compound 1-methyl-1-ketenylcyclobutanone **10** (R^1 = R^2 = R^3 = H, R^4 = Me) to the 5-spirocyclopropyl-$\Delta^{\alpha,\beta}$-butanolide **11** (R^1 = R^2 = R^3 = H; R^4 = Me) was studied computationally by MNDO techniques. Using this procedure, the geometries of the starting 2-methyl-2-ketenylcyclobutanone and the product spirolactone were first minimized, and various interconversion pathways were explored until a true transition state was located. The results of these studies are shown below, and the relevant bond lengths and carbon–carbon internuclear distances for the calculated structures labeled. A number of interesting features are apparent in the proposed transition state shown in eq 7. First, the new carbon–oxygen bond generated by the interaction of the carbonyl oxygen of the cyclobutanone (O1) and the carbonyl carbon of the ketene (C8) is almost completely formed in the transition state. At the same time, there is considerable lengthening of the C3C5 bond and a concurrent decrease in the C3C5 distance. In fact, these distances become almost equal in the calculated transition-state structure. Finally, charge density calculations show that the calculated transition state is dipolar with O9, C7, and O1 acquiring partial negative charges while C8 and C2 are partially positively charged. It appears from the calculations, that the structure shown in eq 7 represents a true transition state, and no evidence of interme-

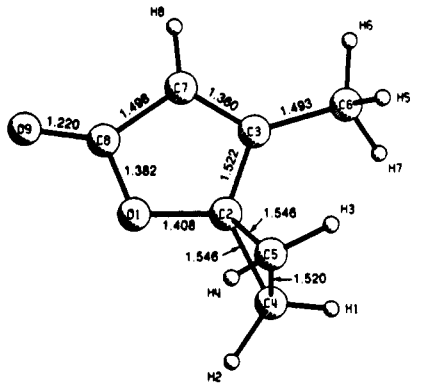
(20) (a) Frost, A. A.; Pearson, R. G. In *Kinetics and Mechanism*; John Wiley and Sons: New York, 1968; Chapter 7. (b) Pearson, R. G. *J. Chem. Phys.* **1952**, *20*, 1478.



Ketene



Transition State

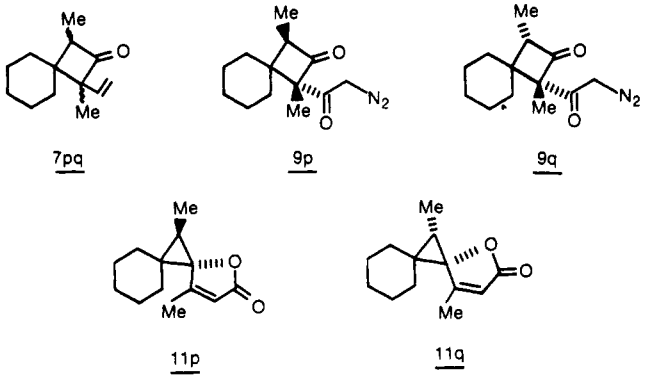


Lactone

(7)

diates along the reaction path was discovered. It is interesting that the structure of the calculated transition state for the rearrangement is quite similar to that proposed on the basis of the kinetic studies except that the former predicts that there should be considerable simultaneous carbon–carbon bond breaking and bond reformation within the four-membered ring as the ketene moiety and the cyclobutanone interact.

In order to study the rearrangement in a stereochemically labeled system, not containing a bicyclic ring system, the diazo ketones **9p,q** were prepared by the cycloaddition of ethylidene cyclohexane with methyl vinyl ketene to yield the epimeric vinyl cyclobutanones **7p,q**, which were subsequently transformed in the usual fashion. Using this procedure, the diazo ketones **9p,q** were isolated as a 1:2.6 epimeric mixture. Unfortunately, although the epimers could easily be separated by flash column chromatography, the respective stereochemistries could not be assigned with confidence by simple NMR spectroscopic analysis because of badly overlapping resonances. For this reason, the respective purified diazo ketones were each thermally converted directly to the spirolactones **11p** and **11q**. Once again, the transformation was completely stereospecific. Examination of the proposed lactone structures suggested that NOE studies should be useful in distinguishing between the stereoisomers. In particular, the geometric proximity between the allylic methyl and the syn cyclopropyl methyl groups in **11p** should result in significant signal enhancement. In practice, the lactone produced from the major diazo ketone isomer showed a 2% signal enhancement for the cyclopropyl methyl signal at δ 1.25 when the allylic methyl at δ 2.13 was irradiated and, hence, the structure was assigned as **11p**. No such NOE enhancement was observed for the lactone epimer **11q** because of the increased distance between the nuclear centers. The enhancement was readily detectible using difference NOE techniques. This information, in conjunction with the predicted stereochemical pathway for the rearrangement (i.e., the etheral oxygen of the butenolide ring appears with the same stereochemical configuration relative to the 2,3-substituents on the original four membered ring as in the original ketene moiety) strongly suggests that the stereochemistry of the major diazo ketone epimer is as shown in **9p** and the minor isomer was accordingly assigned as **9q**. With the stereochemistry of the diazo ketones tentatively established in this fashion, the kinetics of the rearrangement were examined in the manner discussed previously. Irradiation of either **9p** and **9q** in MCH at −50 °C generated the respective ketenes, which rearranged thermally upon warming. The respective rate constants measured at −5 °C were 9.0×10^{-5} s^{-1} for the ketene produced from **9p** and 1.04×10^{-3} s^{-1} for that generated from **9q**. The kinetic data are, therefore, consistent with the suggestion that lower rearrangement rates are expected for α-ketenylcyclobutanones which place three alkyl substituents on the same side of the cyclobutanone ring in the transition state for the rearrangement.



In summary, we have prepared a number of 2-(diazoacetyl)cyclobutanone derivatives from the corresponding 2-vinylcyclobutanones in high yields using a three-step procedure. These materials are converted cleanly to 5-spirocyclopropyl-$\Delta^{\alpha,\beta}$-butenolides upon brief heating in xylene solution, and the rearrangement appears to be completely stereospecific. The ethereal oxygen of the product lactone appears in the same configuration relative to the substituents in the 3,4-positions of the original cyclobutanone ring as the diazocarbonyl group of the starting material. While not detected in the thermal rearrangement, α-ketenylcyclobutanones are intermediates and can be generated photochemically and detected spectroscopically. As expected, the ketenes readily convert thermally to the 5-spirocyclopropyl-$\Delta^{\alpha,\beta}$-butenolides. Kinetic studies of the rate of rearrangement of α-ketenylcyclobutanones suggests an ordered, dipolar cyclic transition state. Pre-

liminary MNDO calculations on the nature of the transition state for the rearrangement also support this hypothesis. The proposed transition state also provides a reasonable rationalization for the large rate differences sometimes observed for bicyclic epimeric derivatives in terms of steric substituent compression.

Experimental Section

All melting points were uncorrected. ^{1}H NMR spectra were recorded either at 90 or 250 MHz. ^{13}C NMR spectra were recorded either at 50 or 63 MHz. For ^{13}C spectra the designation of quaternary (q), tertiary (t), secondary (s), primary (p) when reported were determined using a DEPT pulse sequence.

General Procedure for the Preparation of α-Vinylcyclobutanones. In general, the technique employed was similar to that described by Dreiding and co-workers.[12g] An illustrative procedure is provided for the preparation of an epimeric mixture of 8-methyl-8-vinylbicyclo[5.2.0]nonan-9-one **7c,d**: A 450-mL stainless steel autoclave was charged with 86.5 g (0.9 mol) of cycloheptene, 15.93 g (0.16 mol) of triethylamine, and 17.78 g (0.15 mol) of tiglic acid chloride. The bomb was sealed and heated with stirring to 150 °C for 4 h. After cooling, the reaction mixture was diluted with 200 mL of water and 200 mL of hexane. The aqueous phase was extracted three times with 100 mL of hexane, and the combined organic phases were washed with 5% HCl, water, and saturated $NaHCO_3$. After drying ($MgSO_4$), the solvent was evaporated and the residue was distilled using a Kugelrohr apparatus (80–140 °C, 1 Torr). The distillate was purified by flash column chromatography (silica gel, ethyl acetate–hexane, 1:9). The crude yield of >95% pure product was 48%. The product **7c,d** was isolated as a 3:1 mixture of isomers which was utilized without separation. It is assumed by analogy with similar systems[12g] and from analysis of the spectral data of the mixture that the major isomer **7c** has the methyl group in the endo position of the bicyclic system: ^{1}H NMR (250 MHz, $CDCl_3$) δ 5.91 (dd, J_1 = 17.3 Hz, J_2 = 10.4 Hz) and 5.73 (dd, J_1 = 17.6 Hz, J_2 = 10.7 Hz) (1 H), 5.16 (dd, J_1 = 17.6 Hz, J_2 = 1.5 Hz) and 5.07 (J_1 = 17.3 Hz, J_2 = 0.8 Hz) (1 H), 5.09 (dd, J_1 = 10.7 Hz, J_2 = 1.5 Hz) and 5.03 (dd, J_1 = 10.4 Hz, J_2 = 0.8 Hz) (1 H), 3.65 (m, 1 H), 2.49 (ddd, J_1 = 12.6 Hz, J_2 = 11.0 Hz, J_3 = 3.8 hz) and 2.29 (ddd, J_1 = 12.9 Hz, J_2 = 10.4 Hz, J_3 = 4.2 Hz) (1 H), 1.90 (m) and 1.52–1.04 (m) (10 H), 1.34 and 1.9 (s, 3 H); IR (CCl_4) 3087, 2927, 2853, 1772, 1630, 1452, 1412, 1370, 1251, 1166, 1066, 994, and 923 cm^{-1}; MS (70 eV) 178 (M^+, 48), 163 ($M^+ - CH_3$, 14), and 82 (100).

1-Vinylbicyclo[4.2.0]octan-8-one (7k). Ethyl 2-(5′-Hexenyl)-2-butenoate. To a preformed solution of lithium diisopropylamide in tetrahydrofuran (THF) prepared from 7 mL of diisopropylamine, 50 mL of THF, and 25 mL of 1.8 M *n*-BuLi was added 10 mL of hexamethylphosphoric triamide dropwise over 10 min at −78 °C. After the mixture was for 30 min at this temperature, 4.8 g (0.042 mol) of ethyl-2-butenoate in 15 mL of THF was added over 10 min, and the mixture was stirred for 15 min. To this mixture was added 8.15 g (0.05 mol) of 6-bromo-1-hexene in a single portion. The reaction was stirred at −78 °C for 3 h, −15 °C for 1h, and room temperature for 0.5 h. The reaction was quenched with NH_4Cl, washed with 10% brine, and dried (Na_2SO_4). The residue after evaporation was distilled to give 3.92 g (48%) of the monoalkylated product **5**: (bp 140 °C, 40 Torr); ^{1}H NMR δ ($CDCl_3$) 6.8 (q, J = 7.5 Hz, 1 H), 5.7 (m, 1 H), 4.9 (m, 2 H), 4.1 (q, J = 6.0 Hz, 2 H), 2.4–1.1 (m, 8 H), 1.8 (d, J = 7.5 Hz, 3 H), 1.3 (t, J = 6.0 Hz, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 167.9, 138.8, 136.9, 133.5, 114.3, 60.2, 33.6, 28.7, 28.4, 26.2, 14.2, 14.1; IR (neat) 3080, 2990, 2940, 2865, 1720, and 1645 cm^{-1}.

Anal. Calcd for $C_{12}H_{20}O_2$: C, 73.43; H, 10.27. Found: C, 73.65; H, 10.26.

Ester **5** (3.5 g, 0.017 mol) was heated with 50 mL of 10% ethanolic KOH for 1 h. Upon cooling, 100 mL of water was added, and the mixture was extracted with CH_2Cl_2. After drying ($MgSO_4$), the solvent was evaporated to yield 2.78 g (93%) of 2-(5′-hexenyl)-2-butenoic acid as a viscous oil. The spectral data indicate that the double bond of the butenoic acid residue had completely isomerized to the α,β-position during the hydrolysis: ^{1}H NMR (90 MHz, $CDCl_3$) δ 12.0 (s, 1 H), 6.9 (q, J = 7.5 Hz, 1 H), 5.7 (m, 1 H), 4.9 (m, 2 H), 2.4–1.0 (m, 8 H), 1.8 (d, J = 7.5 Hz, 3 H); IR (neat) 3500–2400, 3086, 2980, 2935, 2865, 1685, 1640, 1420, and 1290 cm^{-1}.

Anal. Calcd for $C_{10}H_{16}O_2$: C, 71.39; H, 9.59. Found: C, 71.47; H, 9.73.

The acid was mixed with 6.6 mL of distilled oxalyl chloride and stirred at room temperature overnight. The excess oxalyl chloride was evaporated, and the residue was distilled to yield 3.0 g (98%) of 2-(5′-hexenyl)-2-butenoyl chloride: ^{1}H NMR (90 MHz $CDCl_3$) δ 7.2 (q, J = 7.5 Hz, 1 H), 5.7 (m, 1 H), 4.9 (m, 2 H), 2.5–1.0 (m, 8 H), and 1.9 (d, J = 7.5 Hz, 3 H); IR (neat) 3085, 2985, 2935, 2870, 1752, and 1641 cm^{-1}.

Anal. Calcd for $C_{10}H_{15}ClO$: C, 64.34; H, 8.10. Found: C, 64.39; H, 8.21.

A solution of 1.25 g (6.7 mmol) of 2-(5′-hexenyl)-2-butenoyl chloride and 1.0 g (10 mmol) of triethylamine in 125 mL of cyclohexane was sealed in a glass Fisher-Porter tube and heated to 150 °C for 4 days. Upon cooling, 200 mL of water and 200 mL of pentane were added, and the layers were separated. The aqueous phase was extracted with pentane, and the combined organic phase washed with 5% HCl, $NaHCO_3$ solution, and water. After drying ($MgSO_4$), the solvent was distilled carefully through a 30-cm Vigreux column. The residue was distilled at 1 atm in a Kugelrohr apparatus, and the distillate was purified by flash column chromatography (silica gel, hexane–ethyl acetate (19:1)) to yield 465 mg (46%) of 1-vinylbicyclo[4.2.0]octan-8-one, **7k**: ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.8 (dd, J = 18 Hz, J_2 = 10.5 Hz, 1 H), 5.0 (m, 2 H), 2.9 (m, 2 H), 2.5 (m, 1 H), and 2.2–1.0 (m, 8 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 209.2, 138.4, 114.1, 66.6, 47.9, 28.3, 28.0, 25.4, 20.6, and 20.4; IR (neat) 3090, 2980, 2940, 2860, 178–, and 1635 cm^{-1}.

Anal. Calcd for $C_{10}H_{14}O$: C, 79.96; H, 9.39. Found: C, 80.04; H, 9.41.

General Procedure for the Preparation of 2-(2-Diazoacetyl)cyclobutanones. Oxidation Procedure. To a biphasic solution of 5 mmol of the respective 2-vinylcyclobutanone in 20 mL of acetonitrile, 20 mL of CCl_4, and 30 mL of water containing 8.77 g (8.2 equiv) of sodium periodate was added 50 mg (4.4 mol %) of ruthenium trichloride trihydrate. The solution was stirred vigorously for 4 h at 25 °C and diluted with 50 mL of CCl_4. The phases were separated, and the aqueous layer was reextracted with additional CCl_4. The combined organic layers were washed with water and dried ($MgSO_4$). The solvent was evaporated, and the dark residue was redissolved in 100 mL of ether. The acid was removed by extraction (3×) with 50 mL of saturated $NaHCO_3$. After acidification to pH 1, the aqueous phase was extracted with ether. The ether was dried ($MgSO_4$) and removed by distillation. The crude products were used without further purification. The yields ranged from 50 to 90%: IR (neat) 3400–1705 cm^{-1} (–CO_2H).

The crude acids were converted directly to the acid chlorides using the following procedure. The acid (5 mmol) was stirred overnight with 2 mL of freshly distilled oxalyl chloride at room temperature. The oxalyl chloride was evaporated, and the residue was quickly purified by Kugelrohr distillation (80–130 °C, 0.1 mm) to yield the acid chlorides, initially as colorless liquids. These materials were used immediately without further purification. The crude yields ranged from 65 to 90%: IR (neat) 1790–1805, shoulder 1760–1775e cm^{-1}.

Diazomethane was prepared in ether solution by hydrolysis of *N*-methylnitrosourea using aqueous potassium hydroxide as described.[21] The diazomethane solution was dried over potassium hydroxide and used without distillation. The diazomethane titer was determined by titration with benzoic acid in ether.

A general procedure for the preparation of the α-(diazoacetyl)cyclobutanones is as follows: 5 mmol of the corresponding flash-distilled acid chloride was dissolved in 50 mL of ether and added via a syringe pump to a 7.5–10-fold molar excess of diazomethane solution at −10 °C over 30 min. The reaction was then stirred for 1 h at −10 °C and allowed to warm to room temperature. When the solution reached room temperature, the excess diazomethane was removed by bubbling argon. After the diazomethane was removed, the solution of the diazo ketone was concentrated on the rotary evaporator, and the residue was purified by flash column chromatography on silica gel, usually with ethyl ace-

(21) Arndt, F. *Organic Syntheses*; Blatt, A. H., Ed.; John Wiley and Sons: New York, 1943; Collect. Vol II, p 165.

tate–hexane solvent mixtures. A mixture of 5% acetonitrile in toluene was utilized for the separation of the epimers **9e,f** and **9g,h**. The diazo ketones, once purified, were relatively stable although they were light sensitive, particularly in solution.

9a,b: epimeric mixture (3:1); 0.5 g (50%); ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.4 and 5.6 (2 s, 1 H), 3.1 (m, 2 H), 2.1–1.1 (m, 12 H), 1.5 and 1.2 (2 s, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 211.0, 191.4, 75.0, 72.3, 61.7, 58.1, 54.6, 53.5, 44.3, 36.8, 35.4, 30.2, 29.9, 28.5, 28.3, 26.0, 25.9, 25.0, 24.6, 24.2, 23.6, 22.9, 22.2, 21.4, and 15.1; IR (CCl_4) 3110, 2930, 2855, 2109, 1765, 1640, 1350 cm^{-1}.

9c,d: epimeric mixture (2.3;1); 1.7 g (42%); ^{1}H NMR (250 MHz, $CDCl_3$) δ 5.79 and 5.45 (2 s, 1 H), 3.50 (m, 2 H), 3.11 and 2.41 (m, 1 H), 2.14–1.72 and 1.55–1.02 (m, 10 H), 1.48 and 1.23 (2 s, 3 H); ^{13}C NMR (63 MHz, $CDCl_3$) δ 212.8, 210.0, 191.0, 190.7, 73.4, 70.0, 62.3, 58.4, 53.6, 53.5, 43.8, 37.1, 31.9, 31.6, 29.4, 28.2, 27.7, 26.7, 25.7, 25.1, 23.2, 15.2; IR (neat) 3113, 2926, 2854, 2111, 1768, 1627, 1451, 1348, 1153, 1036, 996, 936, 831 cm^{-1}.

Anal. Calcd for $C_{12}H_{16}N_2O_2$: C, 65.43; H, 7.32. Found: C, 65.04; H, 7.35.

9e (major isomer): 0.36 g (47%); mp 51–52 °C; ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.4 (s, 1 H), 3.5–2.8 (m, 2 H), 2.1–0.9 (m, 8 H), 1.3 (s, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 206.4, 191.4, 76.9, 55.7, 54.0, 30.0, 23.9, 22.2, 20.4, 14.5; IR (neat) 3110, 2930, 2860, 2109, 1765, 1630, and 1350 cm^{-1}.

Anal. Calcd for $C_{11}H_{14}N_2O_2$: C, 64.06; H, 6.84. Found: C, 63.98; H, 6.89.

9f (minor isomer): yellow oil; 0.14 g (19%); ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.9 (s, 1 H), 3.5 (m, 1 H), 2.6–0.9 (m, 9 H), 1.6 (s, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 211.1, 191.5, 73.1, 54.2, 51.6, 35.3, 20.9, 23.5, 22.3, 20.5; IR (neat) 3110, 2935, 2855, 2107, 1760, 1620, and 1350 cm^{-1}.

9g (major isomer): 0.73 g (30%); mp 53–56 °C; ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.5 (s, 1 H), 3.8–3.3 (m, 2 H), 2.1–1.2 (m, 6 H), 1.2 (s, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 213.9 190.8, 75.1, 63.8, 54.8, 37.0, 28.8, 27.1, 26.9, 14.1; IR (neat) 3110, 2955, 2870, 2108, 1765, 1625, and 1350 cm^{-1}.

Anal. Calcd for $C_{10}H_{12}N_2O_2$: C, 62.49; H, 6.29. Found: C, 62.24; H, 6.30.

9h (minor isomer): yellow oil; 0.4 g (15%); ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.8 (s, 1 H), 3.6 (m, 1 H), 2.8 (m, 1 H), 2.3–1.2 (m, 6 H), 1.5 (s, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 215.5, 190.9, 71.4, 59.8, 53.5, 44.0, 20.7, 28.9, 26.2, 23.5; IR (neat) 3110, 2965, 2870, 2108, 1765, 1620, and 1350 cm^{-1}.

9i: yellow oil; 1.6 g (66%); ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.6 (s, 1 H), 2.8 (m, 2 H), 2.0–1.0 (m, 10 H), 1.3 (s, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 209.6, 191.6, 74.6, 54.1, 52.6, 39.3, 33.7, 32.1, 25.5, 23.4, 23.1, 16.5; IR (neat) 3110, 2935, 2860, 2109, 1770, 1765, 1620, and 1350 cm^{-1}.

Anal. Calcd for $C_{12}H_{16}N_2O_2$: C, 65.43; H, 7.32. Found: C, 65.55; H, 7.45.

9j: yellow oil; 1.5 g (60%); ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.7 (s, 1 H), 2.9 (m, 2 H), 2.2–1.2 (m, 8 H), 1.4 (s, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 209.3, 191.5, 73.1, 56.9, 53.8, 45.9, 35.2, 34.1, 23.6, 22.9, 17.8; IR (neat) 3115, 2960, 2875, 2109, 1775, 1620, and 1350 cm^{-1}.

Anal. Calcd for $C_{11}H_{14}N_2O_2$: C, 64.06; H, 6.84. Found: C, 63.77; H, 6.68.

9k: yellow oil; 0.5 g (40%); ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.6 (s, 1 H), 2.9 (m, 3 H), 2.3–1.0 (m, 8 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 205.9, 190.7, 73.9, 53.4, 48.9, 27.9, 25.9, 25.4, 20.8, 20.1; IR (neat) 3115, 2940, 2865, 2112, 1775, 1630, and 1360 cm^{-1}.

Anal. Calcd for $C_{10}H_{12}N_2O_2$: C, 62.49; H, 6.29. Found: C, 61.94; H, 6.30.

9l,m: epimeric mixture (1:1); 1.63 g (45%); ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.6 and 5.5 (2 s, 1 H), 3.3–0.7 (m, 14 H), 1.5 and 1.3 (2 s, 3 H); IR (neat) 3110, 2960, 2930, 2860, 2111, 1785, 1625, and 1350 cm^{-1}.

Anal. Calcd for $C_{12}H_{18}N_2O_2$: C, 64.84; H, 8.16. Found: C, 64.11; H, 8.27.

9n: yellow oil; 0.11 g (23%); ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.8 (s, 1 H), 2.9 and 2.5 (AB quartet, J = 18 Hz, 2 H), 2.0–0.7 (m, 11 H), 1.4 (s, 3 H), 1.2 (s, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 209.6, 191.7, 74.3, 54.8, 53.8, 37.6, 36.4, 32.4, 24.9, 23.0, 22.6, 18.0, 14.0; IR (neat) 3120, 2960, 2865, 2110, 1770, 1625, and 1345 cm^{-1}.

9o: yellow oil; 0.11 g (23%); ^{1}H NMR (90 MHz, $CDCl_3$) 5.7 (s, 1 H), 2.7 (m, 2 H), 2.3–0.7 (m, 11 H), 1.4 (s, 3 H), 1.3 (m, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 209.6, 191.7, 74.3, 54.8, 53.8, 37.6, 36.0, 32.4, 24.9, 23.0, 22.6, 18.0, 14.0; IR (neat) 3115, 2960, 2935, 2855, 2110, 1775, 1625, and 1345 cm^{-1}.

General Procedure for the Thermolysis of α-(Diazoacetyl)cyclobutanones. One millimole of the purified diazo ketone was dissolved in 20 mL of xylene and added via a syringe pump over 30 min to 20 mL of xylene at 130 °C. The progress of the thermolysis could be followed by TLC analysis. After the addition, the heating was continued for 30 min. Upon completion of the reaction, the solvent was removed and the lactones were purified by flash column chromatography (silica gel, ethyl acetate–hexane).

11a (major isomer): 56%; ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.7 (m, 1 H), 2.0–1.1 (m, 14 H), 1.8 (d, J = 1.5 Hz, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 172.6, 168.1, 118.0, 74.3, 32.0, 28.7, 26.1, 21.6, 16.6; IR ($CDCl_3$) 2950, 2865, 1730, and 1605 cm^{-1}; UV λ_{max}^{MeOH} (ϵ) 246 nm (10 000); high-resolution MS (70 eV) calcd for $C_{13}H_{18}O_2$ 206.1302, found 206.1305.

11b (minor isomer): 19%; ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.8 (m, 1 H), 2.2–1.1 (m, 14 H), 2.1 (d, J = 1.5 Hz, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 172.8, 168.7, 113.3, 74.2, 28.8, 27.8, 26.4, 21.5, 11.8; IR ($CDCl_3$) 3005 (sh), 2970, 2930 (sh), 2860, 1735, and 1610 cm^{-1}.

11c (major isomer): 58%; mp 103 °C; ^{1}H NMR (250 MHz, $CDCl_3$) δ 5.83 (q, J = 1.3 Hz, 1 H), 2.23 (d, J = 1.3 Hz, 3 H), 2.09–2.07 (m, 12 H); ^{13}C NMR (63 MHz, $CDCl_3$) δ 172.2, 168.3, 118.0, 77.0, 32.8, 32.3, 29.4, 24.4, 17.3; IR (CCl_4) 2959, 2925, 2852, 1759, 1612, 1462, 1385, 1357, 1264, 1177, 1118, 1090, 1012, 991, 935, 908, 840, and 642 cm^{-1}; MS (70 eV) 192 (M^+, 33%).

Anal. Calcd for $C_{12}H_{16}O_2$: C, 74.97; H, 8.38. Found: C, 74.90; H, 8.35.

11d (minor isomer): oil; 26% ^{1}H NMR (250 MHz, $CDCl_3$) δ 5.72 (q, J = 1.0 Hz, 1 H), 1.92–1.35 (m, 12 H), 1.85 (d, J = 1.0 Hz, 3 H); ^{13}C NMR (63 MHz, $CDCl_3$) δ 172.5, 168.1, 119.2, 104.2, 32.2, 29.0, 28.0, 24.2, 11.8; IR (neat) 2922, 2850, 1745, 1619, 1464, 1441, 1384, 1344, 1331, 1264, 1240, 1206, 1170, 1090, 1050, 987, 943, 910, 853, 831, 779, and 731 cm^{-1}; MS (70 eV) 192 (M^+, 89%).

11e (major isomer): 50%; mp 94.5 °C; ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.9 (m, 1 H), 2.2 (d, J = 1.5 Hz, 3 H), 2.1–1.4 (m, 10 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 172.0, 167.9, 118.8, 75.8, 24.9, 20.7, 18.2, 17.5; IR ($CDCl_3$), 2950, 2865, 1730, and 1605 cm^{-1}; UV λ_{max}^{MeOH} (ϵ) 245 nm (13 700); high-resolution MS (70 eV) calcd for $C_{11}H_{14}O_2$ 178.0994, found 178.1041.

11f (minor isomer): oil; 20%; ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.7 (m, 1 H), 2.0–1.3 (m, 10 H), 1.8 (d, J = 1.5 Hz, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) 173.6, 170.0, 113.3, 74.5, 21.1, 21.0, 18.6, 11.9; IR (neat) 2940, 2860, 1730, and 1615 cm^{-1}; high-resolution MS (70 eV) calcd for $C_{11}H_{14}O_2$ 178.0094, found 178.1000.

11g (major isomer): mp 103 °C; 43%; ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.8 (m, 1 H), 2.5–1.7 (m, 8 H), 2.1 (d, J = 1.5 Hz, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 171.4, 168.6, 118.4, 76.9, 36.2, 26.2, 25.6, 16.4; IR ($CDCl_3$) 2970, 2880, 1730, and 1605 cm^{-1}; high-resolution MS (70 eV) calcd for $C_{10}H_{12}O_{12}$ 164.0837, found 164.0838.

11h (minor isomer): mp 73 °C; 23%; ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.7 (m, 1 H), 2.2–.17 (m, 8 H), 1.8 (d, J = 1.5 Hz, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 173.7, 168.4, 113.8, 76.8, 31.3, 26.9, 23.2, 12.3; IR ($CDCl_3$) 2950, 2860, 1735, and 1620 cm^{-1}.

11i: 60%; oil; ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.8 (m, 1 H), 2.1–1.0 (m, 12 H), 2.0 (d, J = 1.5 Hz, 3 H), ^{13}C NMR (50 MHz, $CDCl_3$) δ 172.8, 168.7, 116.6, 76.0, 35.5, 32.6, 31.5, 25.9, 25.8, 25.5, 25.4, 15.3; IR (neat) 2970, 2940, 2860, 1742, and 1615 cm^{-1}; UV λ_{max}^{MeOH} (ϵ) = 246 nm (8300); high-resolution MS (70 eV) calcd for $C_{12}H_{16}O_2$ 192.1149, found 192.1149.

11j: 81%; oil; ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.8 (m, 1 H), 2.3–1.4 (m, 10 H), 2.0 (d, J = 1.5 Hz, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 172.0, 168.6, 116.2, 75.4, 27.0, 33.9, 32.9, 27.1, 26.8, 25.6, 14.0; IR (neat) 2960, 2870, 1750, and 1615 cm^{-1}; UV λ_{max}^{MeOH} (ϵ) = 242 nm (12 400).

Anal. Calcd for $C_{11}H_{14}O_2$: C, 74.13; H, 7.92. Found: C, 73.99; H, 7.98.

11k: 55%; oil; ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.7 (d, J = 1.5 Hz, 1 H), 2.9 (m, 1 H), 2.3–0.9 (m, 10 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 173.1, 172.8, 115.1, 73.7, 29.2, 26.1, 25.9, 25.5, 24.2, 15.3; IR ($CDCl_3$) 3120, 2940, 2870, 1740, and 1615 cm^{-1}; UV λ_{max}^{MeOH} (ϵ) = 238 nm (17 400); high-resolution MS (70 eV) calcd for $C_{10}H_{12}O_2$ 164.0837, found 164.0840.

11l,m: 77%; epimeric mixture (1:1); oil; ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.8 and 5.7 (2 m, 1 H), 2.2–0.7 (m, 14 H), 2.0 and 1.9 (2 d, J = 1.5 Hz, 3 H); ^{13}C NMR (20 MHz, $CDCl_3$) 173.1, 172.9, 168.7, 167.6, 117.1, 114.3, 31.2, 28.8, 28.3, 27.9, 27.8, 25.1, 22.5, 22.3, 19.8, 17.8, 14.3, 14.1, 13.9, 11.7, 11.6; IR (neat) 2980, 2950, 2860, 1750, and 1620 cm^{-1}.

Anal. Calcd for $C_{12}H_{18}O_2$: C, 74.19; H, 9.34. Found: C, 73.86; H, 9.08.

11n (isomer A): oil; 34%; ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.8 (m, 1 H), 2.0 (d, J = 1.5 Hz, 3 H), 1.7–0.8 (m, 13 H), 1.4 (s, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) 172.8, 168.6, 116.9, 76.0, 35.4, 32.6, 31.8, 27.9, 26.5, 22.6, 19.9, 15.1, 14.0; IR (neat) 2960, 2930, 2870, 1750, and 1615 cm^{-1}.

11o (isomer B): oil; 34%; ^{1}H NMR (90 MHz, $CDCl_3$) δ 5.9 (m, 1 H), 2.1 (d, J = 1.5 Hz, 3 H), 1.7–0.8 (m, 13 H), 1.3 (s, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) 172.8, 168.8, 116.7, 76.3, 36.1, 31.7, 27.0, 26.9, 26.1, 22.6, 19.2, 15.3, 14.0; IR (neat) 2960, 2930, 2870, 1750, and 1615 cm^{-1}.

Ethyl (9-Methyl-10-oxobicyclo[6.2.0]decan-9-yl)acetate (12a,b). A solution containing 49 mg (0.21 mmol) of **9a,b** (isomer ratio 7.3/1 by ^{1}H NMR) in a solution of 7 mL of methylcyclohexane–ethanol (6:1) was placed in a Pyrex tube, degassed with argon by bubbling, and irradiated at −40 °C overnight. The mixture was warmed to room temperature, and the solvent was evaporated. The residue was purified by flash column chromatography (silica gel, ethyl acetate–hexane, 1:4) to yield 32 mg (61%) of **12a,b** as a mixture of epimers in a ratio of 6:1: ^{1}H NMR (250 MHz, $CDCl_3$) δ 4.14 and 4.12 (q, J = 7.2 Hz, 2 H), 3.38 and 3.30 (ddd, J_1 = 12.1 Hz, J_2 = 10.2 Hz, J_3 = 2.1 Hz, 1 H), 2.53 (AB q, J = 15.4 Hz) and 2.46 (s) (2 H), 2.40 and 2.21 (ddd, J_1 = 12.2 Hz, $J_2 \approx$ 10 Hz, J_3 = 1.9 Hz, 1 H), 1.96–1.10 (m, 12 H), 1.41 and 1.07 (s, 3 H), 1.25 and 1.24 (t, J = 7.1 Hz, 3 H); IR (neat) 2927, 2857, 1773, 1738, 1464, 1370, 1344, 1278, 1225, 1185, 1161, 1110, 1033, 982, 854, and 754 cm^{-1}; high-resolution MS (70 eV) calcd for $C_{15}H_{24}O_3$ 252.1735, found 252.1758.

Anal. Calcd for $C_{15}H_{24}O_3$: C, 71.39; H, 9.59. Found: C, 71.12; H, 9.40.

***exo*-6-(Carbethoxymethyl)-*endo*-6-methylbicyclo[3.2.0]heptan-7-one (12g).** Into 7 mL of a mixture of methylcyclohexane–ethanol (6:1) in a Pyrex tube was placed 40 mg (0.21 mmol) of diazo ketone **9g** (major isomer), and the solution was degassed with argon. The tube was irradiated (λ > 330 nm) for 16 h at −50 °C. After warmup, the solvent was evaporated and the residue was examined by ^{1}H NMR, which suggested the presence of a single ethyl ester. The crude product was purified by flash column chromatography (silica gel, ethyl acetate–hexane, 1;4) to yield 20 mg (45%) of the ester **12g**: ^{1}H NMR (250 MHz, $CDCl_3$) δ 4.13 (q, J = 7.2 Hz, 2 H), 3.71 (tm, J_t = 8.0 Hz, 1 H), 2.81 (tm, J_t = 8.0 Hz, 1 H), 2.65 and 2.40 (AB q, J = 14.8 Hz, 2 H), 2.0 (m, 1 H), 1.98–1.27 (m, 5 H), 1.25 (t, J = 7.2 Hz, 3 H) 0.98 (s, 3 H); ^{13}C NMR (63 MHz, $CDCl_3$) δ 218.4 (q), 170.6 (q) 62.1 (t), 60.9 (q), 60.6 (s), 42.0 (s), 40.2 (t), 28.6, 27.6, 26.9 (s), 14.2, and 13.7 (p); IR (CCl_4), 2971, 2894, 1785, 1747, 1558, 1451, 1375, 1236, 1199, 1154, and 1037 cm^{-1}.

Anal. Calcd for $C_{12}H_{18}O_3$: C, 68.55; H, 8.63. Found: C, 68.36; H, 8.64.

***exo*-6-Methyl-*endo*-6-(carbethoxymethyl)bicyclo[3.2.0]heptan-7-one (12h).** The irradiation was conducted in the same manner as described for **9g** using 39 mg (0.20 mmol) of **9h**. The photolysis residue was purified by flash column chromatography to yield 15 mg (35%) of the ester **12h**. None of the epimeric ester **12g** was detected in the crude photolysate: ^{1}H NMR (250 MHz, $CDCl_3$) δ 4.16 (q, J = 7.1 Hz, 2 H), 3.76 (tm, J_t = 7.6 Hz, 1 H), 2.68 (tm, J_t = 7.7 Hz, 1 H), 2.45 and 2.37 (AB q, J = 16.0 Hz, 2 H), 2.06 (m, 1 H), 2.00–1.32 (m, 5 H), 1.37 (s, 3 H), 1.18 (t, J = 7.1 Hz, 3 H); ^{13}C NMR (63 MHz, $CDCl_3$) δ 217.8 (q), 170.9 (q), 61.2 (t) 60.4 (s), 60.3 (q), 42.3 (t), 33.2 (s), 28.8 (s), 28.3 (s), 26.6 (s), 22.2 (p), and 14.2 (p); IR (CCl_4) 2960, 2872, 1770, 1733, 1449, 1411, 1367, 1342, 1267, 1232, 1194, 1151, 1095, 1053, 997, and 994 cm^{-1}; MS (70 eV) 210 (M^+, 2.3) 164 (M^+ − OEt, 10.4), 142 (M^+ − C_5H_6, 100%, 114 (M^+ − CO_2Et; high-resolution MS (70 eV) calcd for $C_{12}H_{18}O_3$ 210.1265, found 210.1246.

***exo*-7-(Carbethoxymethyl)-*endo*-7-methylbicyclo[4.2.0]octan-8-one (12e).** A solution of 57 mg of the major diazo ketone isomer **9e** in 7 mL of (methylcyclohexane–ethanol (6:1)) was irradiated as described above. The residue, which contained a single ester, was chromatographed (silica gel, ethyl acetate–hexane, 1:4) to yield 36 mg (56%) of the ester **12e** as an oil: ^{1}H NMR (250 MHz, $CDCl_3$) δ 4.12 (q, J = 7.1 Hz, 2 H), 3.55 (m, 1 H), 2.65 and 2.49 (AB q, J = 14.9 Hz, 2 H), 2.40 (m, 1 H), 1.89 (m, 2 H), 1.52 (m, 3 H), 1.23 (m, 3 H), 1.26 (t, J = 7.1 Hz, 3 H), and 1.15 (s, 3 H); ^{13}C NMR (63 MHz, $CDCl_3$) δ 212.9, 171.1, 62.9, 60.6, 52.8, 43.0, 32.3, 23.5, 22.0, 21.8, 20.6, 15.1, and 14.2; IR (film) 2939, 2864, 1769, 1732, 1451, 1370, 1451, 1370, 1317, 1192, 1105, 1031, 976, 918, and 835 cm^{-1}; MS (70 eV) 224 (M^+, weak), 196 (M^+ − CO, 0.2), 179 (M^+ − OEt, 1.7), 151 (M^+ − CO_2Et, 6.2), 29 (100).

Anal. Calcd for $C_{13}H_{20}O_3$: C, 69.61; H, 8.99. Found: C, 68.83; H, 8.80.

***exo*-7-Methyl-*endo*-7-(carbethoxymethyl)bicyclo[4.2.0]heptan-8-one (12f).** A solution of 50 mg of the minor diazoacetyl isomer in 7 mL of methylcyclohexane–ethanol (6:1) was irradiated as described for **9e**. Evaporation of the solvent yielded 32 mg (60%) of the ester **12f** and a small amount of the lactone **11f**. **12f**: ^{1}H NMR (250 MHz, $CDCl_3$) δ 4.12 (q, J = 7.1 Hz, 2 H), 3.64 (tm, J_t = 99.2 Hz, 1 H), 2.64 and 2.42 (AB q, J = 16.6 Hz, 2 H), tm, J_t = 7.8 Hz, 1 H), 2.01 (m, 2 H), 1.55 (m, 3 H), 1.07 (m, 3 H), 1.48 (s, 3 H), and 1.25 (t, J = 7.1 Hz, 3 H); ^{13}C NMR (250 MHz, $CDCl_3$) δ 212.4, 171.2, 61.4, 60.4, 52.5, 35.1, 34.2, 24.9, 23.4, 22.2, 22.1, 20.3, and 14.2; IR (CCl_4) 2941, 2866, 1769, 1738, 1452, 1422, 1371, 1346, 1284, 1264, 1185, 1160, 1095, 1040, 1016, 975, and 937 cm^{-1}; MS (70 eV) 224 (M^+, weak), 196 (M^+ − CO, 0.3), 151 (M^+ − CO_2Et, 10), and 29 (100).

(*E*)- and (*Z*)-2,4-Dimethyl-2-(2-diazoacetyl)spiro[3.5]nonan-3-one (9p,q). Into a stainless steel autoclave was placed 25.0 g (0.23 mol) of ethylidenecyclohexane, 4.48 g (0.38 mol) of tiglic acid chloride, and 4.21 g (0.42 mol) of triethylamine. The bomb was sealed and heated for 4 h at 150 °C. After dilution of the cooled reaction mixture with water, the aqueous phase was extracted with pentane. The combined organic phases were washed with 5% HCl and saturated $NaHCO_3$ and dried ($MgSO_4$). The solvent was distilled, and the residue was transferred by Kugelrohr distillation (80–140 °C, 1 mm) to yield 2.1 g of crude product which was further purified by flash column chromatography (ethyl acetate–hexanes, 1:9) to yield 600 mg of an epimeric mixture of vinylcyclobutanones **7pq**, which was about 85% pure (GLPC analysis). Because of the low yield in this reaction, the mixture was used without further purification: ^{1}H NMR (250 MHz, $CDCl_3$) δ 5.95 [(dd, J_1 = 10.6 Hz, J_2 = 6.8 Hz) and 5.83 (dd, J_1 = 10.7 Hz, J_2 = 6.7 Hz, 1 H)], 5.09 (m, 2 H), 3.13 and 3.08 (q, J = 7.4 Hz, 1 H), 2.11–1.17 (m, 10 H), 1.30 and 1.18 (s, 3 H), 1.09 and 1.05 (d, J = 7.4 Hz, 3 H); ^{13}C NMR (63 MHz, $CDCl_3$) δ 214.9 and 213.8 (q), 138.3 and 136.9 (t), 115.2 and 144.4 (s), 69.0 and 67.0 (q), 60.0 and 59.2 (t), 39.9 and 39.5 (q), 35.8 (s), 34.5 (s), 29.7 (s), 28.9 (s), 25.7 (s), 24.5 (s), 24.4 (s), 23.8 (s), 17.4 (p), 16.5 (p), 9.3 (p), and 8.9 (p).

A solution of 0.48 g (0.025 mmol) of the vinylcyclobutanone mixture from above in 100 mL of acetonitrile/CCl_4 (1:1) was stirred with 4.39 g (0.21 mol) of sodium periodate, 58 mg (0.22 mmol) of ruthenium trichloride trihydrate, and 55 mL of water for 90 min at 25 °C. The reaction was processed as described earlier, and the acid was recovered by acidification to pH 1 and reextraction with ether. In this manner 382 mg (73%) of the crude epimeric mixture of acids were isolated, and this was converted without further purification: ^{1}H NMR (250 MHz, $CDCl_3$) δ 3.50 and 3.13 (2 q, J = 7.4 Hz, 1 H), 1.83–1.21 (m, 10 H), 1.45 and 1.33 (2 s, 3 H), 1.23 and 1.15 (2 d, J = 7.4 Hz, 3 H); IR (CCl_4) 3030, 2940, 2857, 1781, 1694, 1452, 1374, 1275, 1131, and 966 cm^{-1}; MS (70 eV) 210 (M^+, 0.8), 182 (M^+ − CO, 1.1), 154 (13), 137 (100); high-resolution MS (70 eV) calcd for $C_{12}H_{18}O_3$ 210.1256, found 210.1219.

The crude acid mixture (296 mg 0.14 mmol) was stirred with 1 mL of oxalyl chloride under argon for 4 h at 25 °C. The excess oxalyl chloride was evaporated, and the residue was flash distilled using a Kugelrohr apparatus (100–120 °C, 0.02 mm) to yield 247 mg (77%) of crude (*E*,*Z*)-2,4-dimethyl-2-(chlorocarbonyl)spiro[3.5]nonan-3-one, which was converted directly to the corresponding diazo ketones **9p,q** without further purification: ^{1}H NMR (250 MHz, $CDCl_3$) δ 3.42 and 3.18 (2 q, J = 7.5 Hz, 1 H), 2.06–1.25 (m, 10 H), 1.59 and 1.48 (2 s, 3 H), 1.22 and 1.21 (2 d, J = 7.5 Hz, 3 H); IR (film) 2938, 2857, 1784, 1449, 1377, 1209, 1025, 965, 923, and 804 cm^{-1}. The entire quantity of keto acid chloride from above (1.08 mmol) was dissolved in 10 mL of ether

and added dropwise to a solution containing 10.8 mmol of diazomethane in 11 mL of ether at 0 °C, and the mixture was stirred for 30 min. The excess diazomethane was removed with argon, and the product was subjected to repetitive flash column chromatography (1:4 ethyl acetate–hexane) in order to separate the epimeric diazo ketones. In this manner 36 mg (14%) of the *Z* isomer **9q** and 77 mg (36%) of the *E* isomer (**9p**) were isolated. **9p**: ^{1}H NMR (250 MHz, $CDCl_3$) δ 5.46 (s, 1 H), 3.11 (q, J = 7.5 Hz, 1 H), 1.85–1.24 (m, 10 H), 1.31 (s, 3 H) and 1.18 (d, J = 7.5 Hz, 3 H); ^{13}C NMR (63 MHz, $CDCl_3$) δ 212.5, 192.8, 75.9, 61.2, 54.5, 42.0, 36.2, 28.1, 25.3, 24.0, 23.8, 15.7, 10.7; IR (CCl_4) 3115, 2974, 2936, 2857, 2108, 1764, 1627, 1449, 1342, 1258, 1223, 1141, 1097, 1045, 1027, 964, 933, and 879 cm^{-1}.

Z isomer, **9q**: ^{1}H NMR (250 MHz, $CDCl_3$) δ 5.56 (m, 1 H), 3.16 (q, J = 7.3 Hz, 1 H), 1.84–1.18 (m, 10 H), 1.40 (s, 3 H), 1.17 (d, J = 7.3 Hz, 3 H); ^{13}C NMR (63 MHz, $CDCl_3$) δ 213.0, 191.8, 72.7, 58.6, 54.4, 41.7, 34.4, 29.4, 25.4, 23.9, 23.4, 17.5, 10.0; IR (CCl_4) 3115, 2937, 2856, 2109, 1762, 1624, 1454, 1368, 1345, 1260, 1244, 1226, 1149, 1118, 1037, 1009, 976, 914, 879, and 844 cm^{-1}.

Pyrolysis of **9q**: Into a flask was placed 10 mL of xylene, and the solvent was heated to reflux before a solution of 30 mg of **9p** dissolved in 5 mL of xylene was added dropwise. After being heated for 30 min at reflux, the mixture was cooled and the solvent was evaporated to yield 23 mg of the spirocyclopropyl lactone **11p**. The stereochemistry was assigned on the basis of a 2% NOE observed for the cyclopropyl methyl group upon irradiation of the allylic methyl group of the $\Delta^{\alpha,\beta}$-butenolide: ^{1}H NMR (250 MHz, $CDCl_3$) δ 5.80 (q, J = 1.5 Hz, 1 H), 2.13 (d, J = 1.5 Hz, 3 H), 1.86 (q, J = 6.9 Hz, 1 H), 1.62–1.23 (m, 10 H), 1.25 (d, J = 6.9 Hz, 3 H); ^{13}C NMR (63 MHz, DEPT, $CDCl_3$) δ 172.9 (q), 168.0 (q), 117.5 (t), 77.7 (q), 39.0 (q), 34.4 (s), 26.2 (s), 26.0 (s), 25.6 (s), 25.4 (s), 33.3 (t), 17.0 (p), 8.5 (p); IR (CCl_4) 2932, 2855, 1757, 1614, 1445, 1386, 1325, 1301, 1275, 1257, 1233, 1203, 1177, 1143, 1099, 1065, 1026, 1009, 994, 972, 937, 923, 861, and 842 cm^{-1}; MS (70 eV) 206 (M^+, 35), 191 (M^+ – Me, 5.6), 177 (M^+ – HCO, 7.7), 125 (100).

Pyrolysis of **9q**: The same procedure was employed as above using 35 mg (0.15 mmol) of the diazo ketone **9q**. After evaporation of the solvent 31 mg (89%) of the lactone **11q** was isolated. TLC analysis showed that the reaction was stereospecific and none of the isomeric lactone **11p** was detected: **11q**: ^{1}H NMR (250 MHz, $CDCl_3$) δ 5.76 (q, J = 1.4 Hz, 1 H), 2.01 (d, J = 1.4 Hz, 3 H), 1.96–1.17 (m, 11 H), 1.12 (d, J = 6.4 Hz, 3 H); ^{13}C NMR (63 MHz, $CDCl_3$) δ 173.3, 169.7, 115.5, 77.1, 37.8, 33.4, 31.0, 27.3, 26.1, 25.5, 25.2, 15.3 and 7.8; IR (CCl_4) 2932, 2855, 1757, 1611, 1443, 1380, 1320, 1274, 1255, 1173, 1100, 967, 935, 919, and 842 cm^{-1}; MS (70 eV) 206 (M^+, 10), 191 (M^+ – HCO, 2.7), 125 (100). Consistent with the proposed stereochemical assignment, no NOE enhancement of the cyclopropyl methyl signal was observed upon irradiation of the allylic methyl group at δ 2.01. However, irradiation of this signal resulted on a 6% enhancement of the geometrically proximate vinyl hydrogen signal at δ 5.76.

The Photochemical Generation and Thermal Rearrangement of α-Ketenylcyclobutanones. Diazo ketones were dissolved in 20 mL of dry methylcyclohexane (c = (5–10) × 10^{-3} M) placed in a Pyrex tube, sealed, and thoroughly degassed with argon. The tube was placed in a quartz dewar filled with methanol, surrounded by a circular filter tube of Corning 332 glass (transmission at 340 nm, 10%), and cooled to between –40 and –50 °C with a FTS systems immersion cooler. The apparatus was then placed in a Rayonet photochemical reactor (Southern New England Ultraviolet) fitted with 14 3500-Å lamps and irradiated until the diazo band (2110 cm^{-1}) of the starting material was no longer detectable by IR (12–16 h). The tube was then removed and placed in a thermostated bath, and samples were withdrawn at intervals and analyzed by IR. The rate of disappearance of ketene was monitored by plotting ln ($A - A_0$) for the ketene band at 2120 cm^{-1} in the IR versus time. Solvent studies were conducted in a similar fashion. In this regard, the range of useful solvents is limited by the reactivity of the ketenes and their mode of generation.

Supplementary Material Available: Detailed X-ray spectral data (57 pages). Ordering information is given on any current masthead page.

Experimental Formal Steric Enthalpy. 1. Alkanes and Cycloalkanes

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This study makes a critical evaluation of experimental values of formal steric enthalpies derived from published values of enthalpies of formation of alkanes and cycloalkanes (gas phase, 298 K). These provide primary data for calibration of force fields used in molecular mechanics.

This is the first of four papers describing studies of experimental formal steric enthalpies. These are derived from enthalpies of formation in the gas phase at 25 °C and are based on compilations by Cox and Pilcher[1] as revised by Pedley, Naylor, and Kirby[2,3] and from compilations of Stull, Westrum, and Sinke.[4] A few data are from other sources as listed.

Formal steric enthalpy (FSE) is a precisely defined measure of the steric component of the enthalpy of formation. It is the component that is to be computed by a molecular mechanics calculation. The raw energy value computed in a molecular mechanics calculation may be designated as the steric energy (SE). SE values are of limited utility for estimating enthalpies of formation since they vary from one force field to another. Procedures are described elsewhere for a simple method to convert SE values derived from any force field to FSE values[5,6] providing that calibration of the force field is based on sound thermodynamic principles.

Equation 1 represents the empirical dissection of the enthalpy of formation of a compound in the gas phase into a bond component and a steric component. It is the basic variant of the traditional representations that are used to correlate thermochemical data.[1,7] Similar equations are successful with other thermochemical quantities, including

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