Fractional atomic coordinates are given in Table III.

Acknowledgment. We are grateful to DGICYT of MEC (Spain) for financial support through Projects 0144-84 and PB87-0388. We thank also "Massó Analitica S.A." for a Research Fellowship (to A.R.), "Atochem España S.A." for providing us with the "Forane 11" (CCl_3F) used in this research, and Mr. D. Turuguet for his helpful comments.

Registry No. 1, 608-93-5; 2, 384-83-8; 3, 2605-69-8; 4, 634-66-2; 5, 97985-54-1; 6, 2136-87-0; 7, 634-90-2; 8, 126278-82-8; 9, 126300-29-6; 10, 95-94-3; 11, 7656-99-7; 12, 2142-30-5; 13, 87-61-6; 14, 61841-45-0; 15, 20020-72-8; 16, 120-82-1; 17, 56148-83-5; 18, 27020-90-2; 19, 108-70-3; 20, 567-59-9; 21, 14379-95-4; 22, 50-40-8; 23, 50-75-9; 24, 50-82-8; 25, 50-43-1; 26, 89978-33-6; 27, 86569-86-0; 28, 86569-78-0; 29, 70439-09-7; 30, 23400-04-6; 31, 327-72-0; 32, 130199-73-4; 33, 5002-24-4; 34, 60047-51-0; 35, 130199-74-5; 36, 130199-75-6; 37, 20019-06-1; 38, 130199-76-7; 39, 7401-89-0; CCl_3F, 75-69-4; $AlCl_3$, 7446-70-0.

Supplementary Material Available: Deviations of the atoms from the mean plane of the benzene ring (Table IV), anisotropic thermal parameters (Table V), and a stereoview of the unit cell of **38** (Figure 3) (3 pages); structure factors of **34**, **36**, and **38** (calculated and observed; Table VI) (34 pages). Ordering information is given on any current masthead page.

Reaction of Pyrrolo[1,2-*c*]imidazole Mesomeric Betaines with Diphenylcyclopropenone Derivatives

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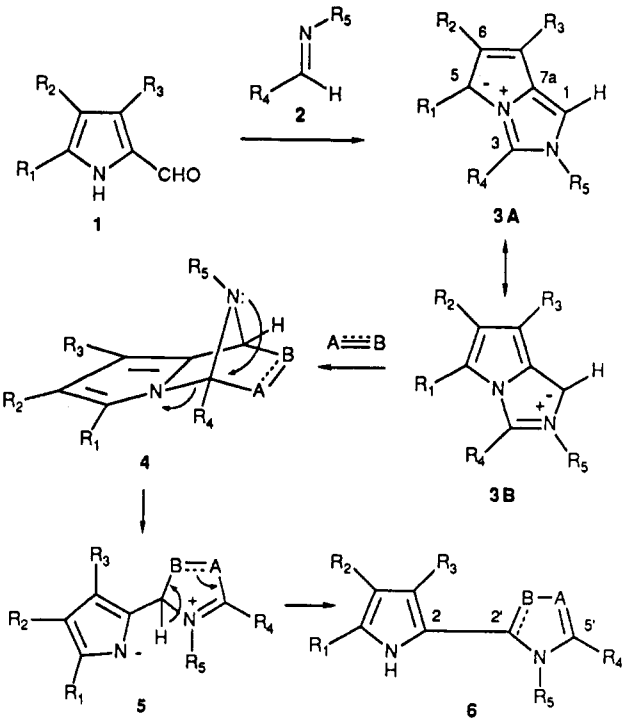
Received April 17, 1990

The cyloaddition reactions of title mesomeric betaines to diphenylcyclopropenone and diphenylcyclopropenethione have been studied. Cycloadditions lead to either 2(1*H*)-pyridone, 2(1*H*)-pyridinethione, or bicyclo[3.1.0]hex-3-en-2-one derivatives. Formation of the bicyclo[3.1.0]hex-3-en-2-ones is highly stereoselective with exclusive formation of C-6 *exo*-alkoxycarbonyl or the *exo*-acetyl diastereoisomer. Diphenylcyclopropenone and its thione enriched with ^{13}C at both the 2- and 3-positions were prepared and used to determine the structures of the cycloaddition products. Possible mechanistic pathways for these reactions are considered and compared with previous postulated mechanisms for the cycloadditions of cyclopropenones to N-heterocycles and enamines.

In our previous work[1] we described a condensation of 2-formylpyrroles **1** with aromatic imines **2** as a general method for the synthesis of a novel class of heteropentalene mesomeric betaines, pyrrolo[1,2-*c*]imidazole mesomeric betaines **3A** ↔ **3B** (Scheme I). We also investigated their participation in 1,3-dipolar cycloaddition reactions with representative acetylenic and olefinic dipolarophiles.[1] Addition to both classes of dipolarophiles was highly periselective, with the dipolarophile adding exclusively across the 1,3-azomethine ylide dipole **3B**. The products of cycloaddition, 2,2′-bipyrroles and 2′,3′-dihydro-2,2′-bipyrroles **6**, were assumed to be formed through the rearrangement of the expected cycloadduct **4** via zwitterionic intermediate **5**.

Due to their exceptional structural characteristics, cyclopropenone derivatives and their thiono analogues have been used as indispensable intermediates in reactions wih diverse classes of organic molecules,[2] including several classes of heterocyclic mesomeric betaines, such as mesoionic compounds[3] and conjugated heterocyclic *N*-ylides.[4] However, the chemistry of cycloadditions of cyclopropenones to heteropentalene mesomeric betaines have been investigated only under high pressure.[5] As part of our continuing interest in the properties of the title mesomeric betaines, we have studied their reactivity toward diphenylcyclopropenone (**7a**) and diphenylcyclopropenethione (**7b**). On the basis of the established reactivity pattern of **3** with acetylenic and olefinic dipolarophiles, the following types of diphenylcyclopropenone cycloaddition pathways were regarded as plausible (Scheme II): addition

Scheme I



across the C–C double bond would afford cycloadduct **8**, which could undergo further rearrangement via dipolar

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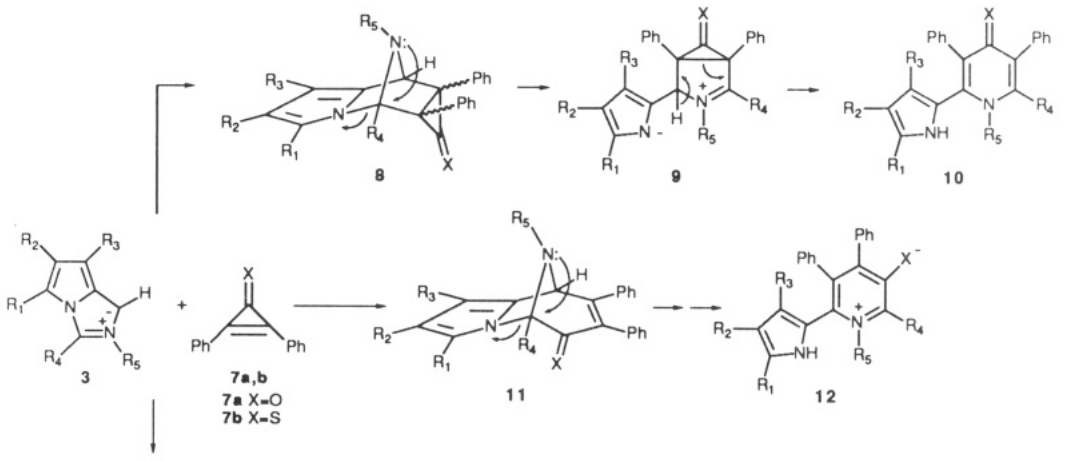
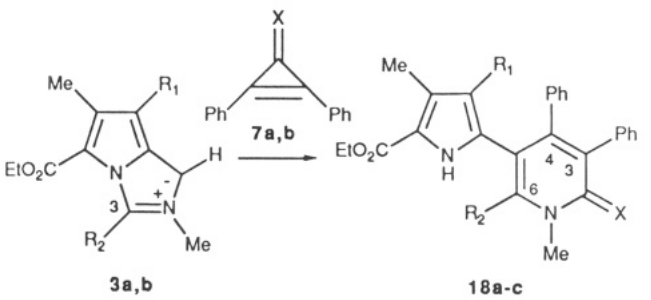
(1) Musicki, B. *J. Org. Chem.* **1990**, *55*, 910.

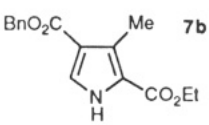
0022-3263/91/1956-0110$02.50/0

Scheme II



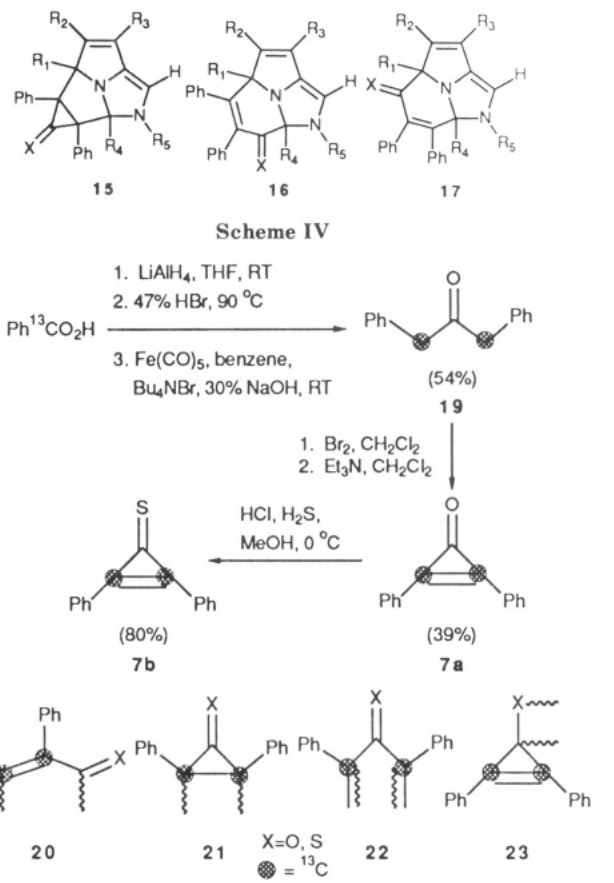
Scheme III



compd	R_1	R_2	compd	X	compd	yields, %
3a	COOEt	Ph	**7a**	O	**18a**	55
3a	COOEt	Ph	**7b**	S	**18b**	83
3b	COOBn		**7b**	S	**18c**	28

species **9** to 4(1*H*)-pyridone **10**; C–C insertion reaction across carbons 1 and 2 of the propenone would afford

Scheme IV



α,β-unsaturated ketones **11** or **13**, which likewise could provide, through skeletal rearrangement, 3(1*H*)-pyridones **12** or **14**, respectively. Considerig that pyrrolo[1,3-*c*]-imidazole mesomeric betaines could potentially participate in the same 1,3-dipolar cycloaddition reactions as 1,3-azomethine ylide dipoles **3A**, three different diazacyclazine derivatives **15**–**17** were also regarded as possible reaction products.

Results and Discussions

The mesomeric betaine **3a** reacted readily with diphenylcyclopropenone in refluxing benzene over 7 h to afford a product whose unexpected structure was assigned as 2(1*H*)-pyridone **18a** on the basis of ^{13}C spectral data of ^{13}C-enriched samples of **18a**, analytical data, and chemical transformations (Scheme III). Similarly, 2(1*H*)-pyridinethiones **18b** and **18c** were isolated upon the re-

(2) For the reviews on the reactivity of cyclopropenes (including cyclopropenones), see: (a) Potts, K. T.; Baum, J. S. *Chem. Rev.* **1974**, *74*, 189. (b) Eicher, T.; Weber, J. *Top. Curr. Chem.* **1975**, *57*, 1. (c) Deem, M. L. *Synthesis* **1982**, 701.

(3) Potts, K. T. In *1,3-Dipolar Cycloaddition Chemistry*; Padwa, A., Ed.; John Wiley & Sons: New York, 1984; Vol. II, pp 1–82.

(4) (a) Eicher, T.; Hansen, A. *Tetrahedron Lett.* **1967**, 1169. (b) Matsumoto, K.; Lown, J. W. *J. Org. Chem.* **1971**, *36*, 1405. (c) Sasaki, T.; Kanematsu, K.; Kakehi, A. *Ibid.* **1971**, *36*, 2451. (d) Kascheres, A.; Marchi, D., Jr. *Ibid.* **1975**, *40*, 2985. (e) Kascheres, A.; Marchi, D., Jr.; Rodrigues, J. A. R. *Ibid.* **1978**, *43*, 2892. (f) Kascheres, A.; Marchi, D., Jr. *J. Chem. Soc., Chem. Commun.* **1976**, 275. (g) Matsumoto, K.; Kono, Y. *Ibid.* **1976**, 1045. (h) Barr, J. J.; Storr, R. C.; Tandon, V. K. *J. Chem. Soc., Perkin Trans. 1* **1980**, 1147. (i) Hori, M.; Kataoka, T.; Shimizu, H., Imai, E.; Tanaka, K.; Kimura, K.; Hashimoto, Y.; Inagaki, S.; Goto, N.; Kido, M. *Ibid.* **1987**, 2531. (j) Tsuge, O.; Shimoharada, H.; Noguchi, M. *Chem. Lett.* **1981**, 1493.

(5) Matsumoto, K.; Hashimoto, S.; Uchida, T.; Acheson, R. M. *Heterocycles* **1982**, *19*, 1483.

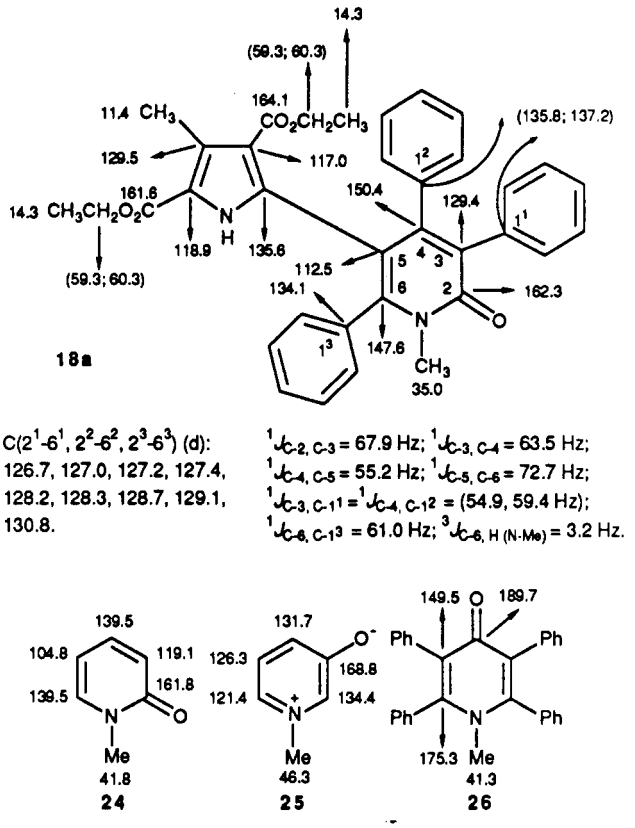
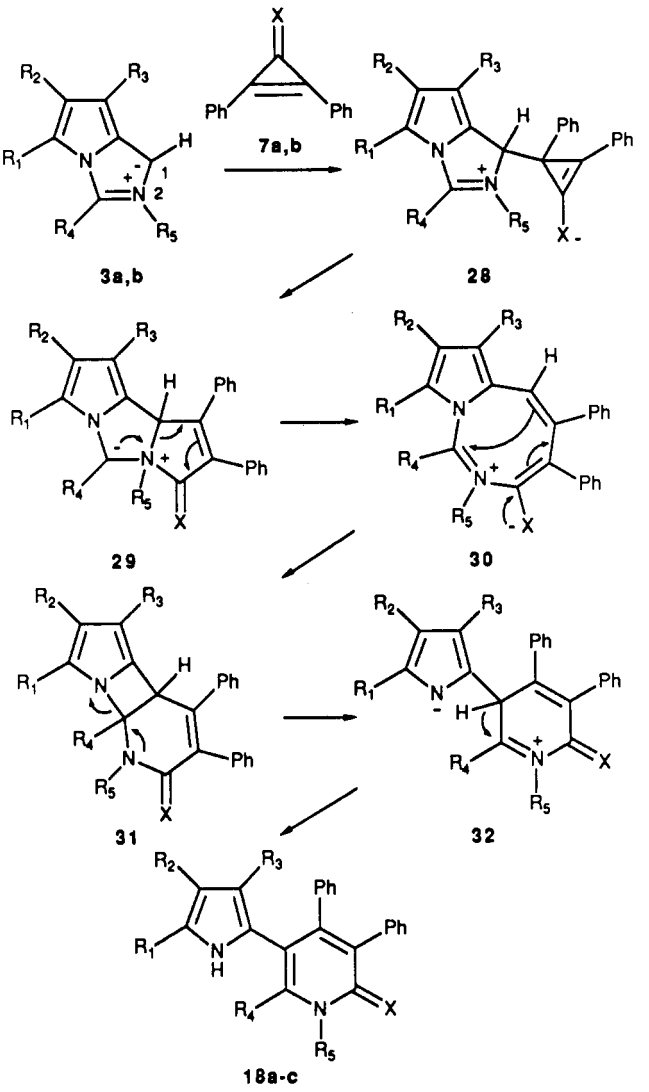


Figure 1. ^{13}C NMR data (75 MHz) of 2(1*H*)-pyridone (**18a**). Chemical shifts are given in ppm in reference to $CDCl_3$ (77.00 ppm).

action of mesomeric betaines **3a** and **3b** with diphenylcyclopropenethione, respectively.[6] Although the spectral data of cycloadducts of mesomeric betaines **3a,b** with **7a,b** did indicate pyridone structures, the location of the C=O or C=S group was ambigous. In order to distinguish between postulated pyridone structures **10**, **12**, **14**, and the isomeric **18a**, it was clear that one would have to relay on the corresponding ^{13}C NMR spectra. In that regard, we prepared the following ^{13}C-enriched samples: pyridone **18a** and pyrridinethiones **18b,c** doubly labeled at the 3- and 4-positions; singly labeled **18a** and **18b** at the 6-position. The necessary ^{13}C-labeled precursors, diphenylcyclopropenone and its thione, labeled at C-2 and C-3, were prepared according to the reaction sequence[7] shown in the Scheme IV. Starting from the readily available 99% ^{13}C-enriched benzoic acid, 99% doubly labeled dibenzyl ketone (**19**) was prepared in 54% overall yield. In subsequent conversions of **19** to **7a** to **7b**, 20% doubly enriched dibenzyl ketone was used. The reason for the use of doubly labeled **7a,b** in our experiments was that it could provide,

Scheme V



through ^{13}C chemical shift values and C–C coupling constants, a general and simple means to distinguish between the different types of cyclopropenone and cyclopropenethione cycloaddition products, **20–23** (Scheme IV). Pyridones **18a** and **18b** singly enriched at the C-6 were prepared by reaction of ^{13}C-labeled mesomeric betaine **3a** at the C-3[1] with **7a** and **7b**, respectively. The results of ^{13}C NMR measurements are shown in Figure 1. In a single enriched sample **18a**, $^{1}J_{CC}$ coupling constants were observed between the labeled carbon at 147.6 ppm and the carbons at 134.1 and 112.5 ppm, whereas in the doubly enriched sample of **18a**, two labeled carbon atoms at 150.4 and 129.4 ppm displayed four $^{1}J_{CC}$ coupling constants (in addition to self coupling) with carbons at 162.3, 137.2, 135.8, and 112.5 ppm. Since the ^{13}C signal for the carbonyl carbon in 2(1*H*)-, 3(1*H*)-, and 4(1*H*)-pyridones appeared at 160–185 ppm, the 2(1*H*)-pyridone structure **18a** was the only possible structure among those considered. For comparison, ^{13}C NMR data of pyridone model systems **24–26**[12] are also shown in Figure 1. Structural similarity between **18a** and **18b** was further established by conversion of pyridone **18a** into pyridinethione **18b** by reaction with phosphorus pentasulfide in refluxing toluene. The pyridinethione **18b** was also readily converted into the corre-

(6) An excess of cyclopropenone derivatives (1.5–5 equiv) was used in reactions with mesomeric betaines **3a–e** to effect the completion of the cycloadditions.

(7) Benzyl bromide was obtained according to the procedure for the preparation of 2,2′-bis(bromomethyl)biphenyl in ref 8. For the preparation of dibenzyl ketone, the procedure described in ref 9 was used. Diphenylcyclopropenone was prepared by a modified Favorskii reaction as described in ref 10 with the exception that the final purification step of diphenylcyclopropenone was accomplished by column chromatography (hexanes–EtOAc, 5:1) and not through isolation of the diphenylcyclopropenone bisulfite complex. Diphenylcyclopropenethione was prepared as described in ref 11.

(8) Hall, D. M.; Lesslie, M. S.; Turner, E. E. *J. Chem. Soc.* **1950**, 711.

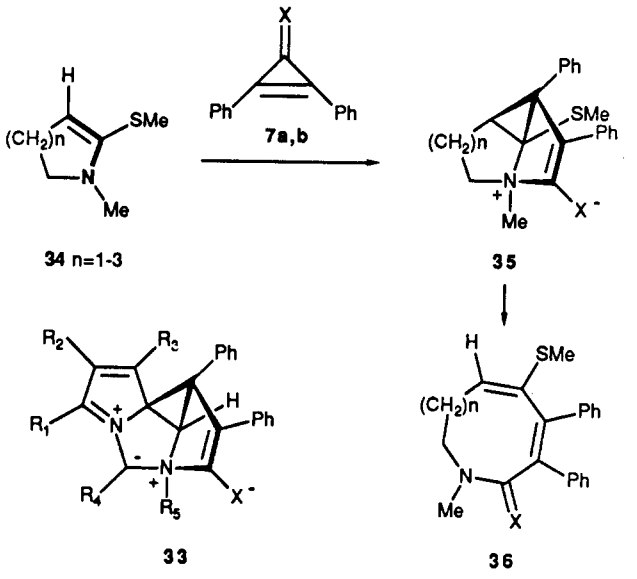
(9) Kimura, Y.; Tomita, Y.; Nakanishi, S.; Otsuji, Y. *Chem. Lett.* **1979**, 321.

(10) Breslow, R.; Posner, J. *Organic Syntheses*; Wiley: New York, 1973; Collect. Vol. V, p 514.

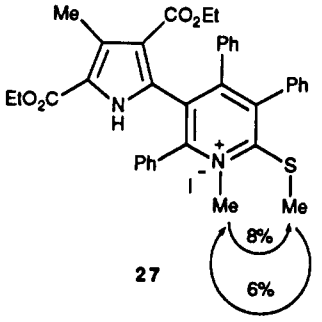
(11) Metzner, P.; Vialle, J. *Bull. Soc. Chim. Fr.* **1972**, 3138.

(12) (a) Vogeli, U.; von Philipsborn, W. *Org. Magn. Reson.* **1973**, *5*, 551. (b) Potts, K. T.; Baum, J.; Houghton, E. *J. Org. Chem.* **1976**, *41*, 818.

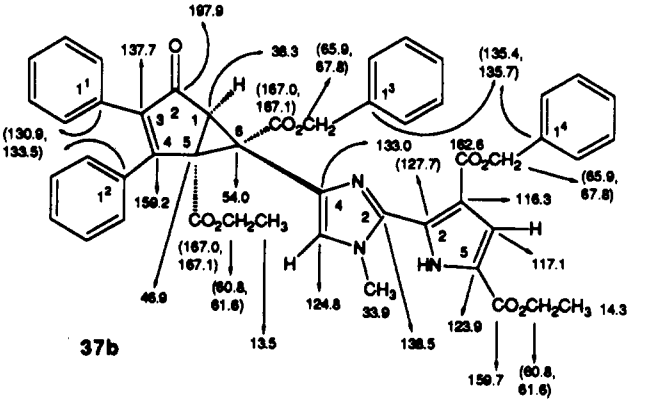
Scheme VI



sponding *S*-methyl derivative **27** by treatment with excess methyliodide in methanol. The location of sulfur at C-2 of pyridinethione **27** was confirmed by the results of the NOE experiments performed on **27**.



One of the possible mechanistic explanations for the formation of 2(1*H*)-pyridone **18a** and 2(1*H*)-pyridinethiones **18b,c** is shown in Scheme V. The condensation was initiated by nucleophilic addition of C-1 of a mesomeric betaine to the C=C bond of cyclopropenone to provide zwitterionic species **28**, followed by the cyclopropenone ring opening in **28** to an intermediate *N*-ylide **29**. Cleavage of the 1,2-bond in **29** would afford pyrrolo[1,2-c][1,3]diazocine derivative **30**, whose valence tautomer **31** could rearrange via intermediate zwitterion **32** to 2(1*H*)-pyridone **18a** or 2(1*H*)-pyridinethiones **18b,c**. Formation of an intermediate **29** through a formal (3 + 2) cycloaddition of diphenylcyclopropenone to the C_1-NMe double bond of mesomeric betaine **3a,b** was reminiscent of cycloaddition of **7a** to N-heteroaromatic compounds such as pyridine, pyrazine, pyridazine, isoquinoline, and their derivatives.[13] These cycloadditions are believed to be initiated by the attack of nitrogen at the cyclopropenone carbonyl carbon (C-1).[2b] However, in the case of mesomeric betaines **3a,b**, primary addition to **7a,b** occurs most likely through C-1 of mesomeric betaine as presented in Scheme I. This is in accord with our previous findings[1] that C-1 of mesomeric betaines **3** possess nucleophilic character.[14] Al alternative



C(2^1-6^1, 2^2-6^2, 2^3-6^3, 2^4-6^4) (d):
128.0, 128.0, 128.0, 128.1, 128.2, 128.2, 128.2, 128.4, 128.5, 128.9, 129.2, 129.5.

pyrrole part
$^1J_{C-3,H-3}$ = 180.1 Hz;
$^2J_{C-5,H-4}$ = 6.2 Hz;
$^3J_{C-3,H-4}$ = 5.0 Hz.

bicyclo[3,1,0]hex-3-en-2-one part
$^1J_{C-2,C-3}$ = 54.6 Hz; $^1J_{C-3,C-4}$ = 74.6 Hz;
$^1J_{C-4,C-5}$ = 47.3 Hz;
$^1J_{C-3,C-1^1}$ = $^1J_{C-4,C-1^2}$ = (58.1, 59.7 Hz);
$^2J_{C-1,C-3}$ = 17.8 Hz; $^2J_{C-2,C-4}$ = 6.4 Hz;
$^1J_{C-1,H-1}$ = 181.3 Hz; $^3J_{C-3,H-1}$ = 6.4 Hz.

imidazole part
$^1J_{C-5,H-5}$ = 189.7 Hz; $^2J_{C-4,H-5}$ = 8.0 Hz;
$^3J_{C-2,H-5}$ = 8.0 Hz.

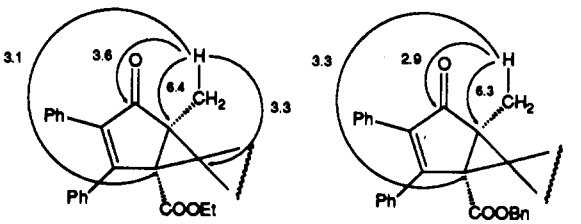
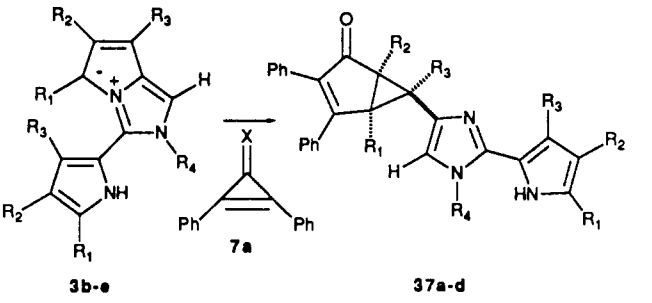


Figure 2. ^{13}C NMR data (125 MHz) of bicyclo[3.1.0]hex-3-en-2-ones (**37a–c**). Chemical shifts are given in ppm in reference to $CDCl_3$ (77.00 ppm). Coupling constants $^2J_{CH}$ and $^3J_{CH}$ for **37a,c** are given in hertz.

Scheme VII



compd	R_1	R_2	R_3	R_4	compd	yields, %
3b	COOEt	Me	COOBn	Me	**37a**	83
3c	COOEt	H	COOBn	Me	**37b**	67
3d	COOBn	Me	COMe	Me	**37c**	70
3e	COOEt	Me	COOBn	Bu	**37d**	72

mechanistic pathway (Scheme VI), however less likely, would involve highly strained and highly charged intermediate **33**, structurally similar to the "primary adducts"[15] **35** isolated upon the reaction of ketene acetals **34** with **7a** and **7b** at room temperature. At elevated temperatures **35** undergoes rearrangement to 2,4-cyclodienamide **36**,[15]

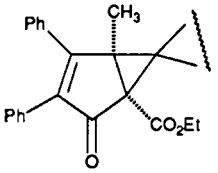
(13) (a) Lown, J. W.; Matsumoto, K. *Can. J. Chem.* **1971**, *49*, 1165. (b) Wadsworth, D. H.; Bender, S. L.; Smith, D. L.; Luss, H. R. *Tetrahedron Lett.* **1981**, 3569. (c) Wadsworth, D. H.; Bender, S. L.; Smith, D. L.; Luss, H. R.; Weidner, C. H. *J. Org. Chem.* **1986**, *51*, 4639.

(14) H-1 of mesomeric betaine **3** undergoes facile exchange with deuterium in acidic media.

(15) (a) Sauer, J.; Krapf, H. *Tetrahedron Lett.* **1969**, 4279. (b) Hirth, M.; Krapf, H.; Riedl, P.; Sauer, J.; Oeser, E. *Chem. Ber.* **1976**, *109*, 562. (c) Krapf, H.; Riedl, P.; Sauer, J. *Ibid.* **1976**, *109*, 576.

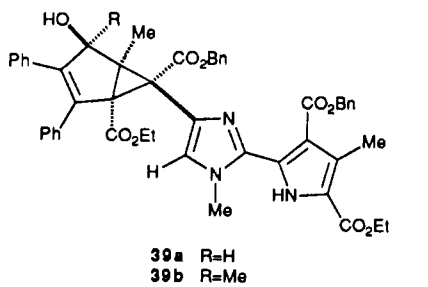
which resembles the intermediate pyrrolo[1,2-*c*][1,3]diazocine derivative **30**.

Surprisingly, the reaction of mesomeric betains **3b–e** with diphenylcyclopropenone in refluxing benzene did not afford the corresponding 2(1*H*)-pyridones. Instead, the structures of the products were identified as bicyclo[3.1.0]hex-3-en-2-one derivatives **37a–b** on the basis of spectral and analytical data (Scheme VII). The principal spectral characteristics are illustrative for **37a**. The UV spectrum indicates the presence of conjugated cyclopentenone system [λ_{max} (log ϵ) (MeOH): 208 (4.78), 263 (4.34), 315 (4.05)]. In the ^{1}H NMR spectrum, a sharp singlet proton resonance corresponding to the imidazole proton was observed at 6.8 ppm. A broad singlet at 8.9 ppm was indicative of an acidic N-H pyrrole hydrogen. The major structural assignment was made, again primarily on the basis of ^{13}C NMR spectral data of the ^{13}C-enriched samples of **37a** and **37b**, which were prepared by the reaction of **3b** and **3c** with ^{13}C doubly labeled diphenylcyclopropenone at the 2- and 3-positions, respectively. The results of ^{13}C measurements are shown in Figure 2. Although the $^3J_{CH}$ = 3.6 and 2.9 Hz values between the hydrogens of the cyclopropyl methyl group and the C=O of cyclopentenone in **37a,c**, respectively, favor structures **37a,c** over **38**,[16] a straightforward assignment of bicyclo[3.1.0]hex-3-en-2-one **37b** stereochemistry was established. Here, $^1J_{CC}$ = 47.3 Hz was observed between the β-enriched carbon (C-4) of cyclopentenone at 159.2 ppm and the cyclopropane carbon C-5 at 46.9 ppm, whereas $^2J_{CC}$ = 17.8 Hz was observed between the cyclopentenone α-carbon (C-3) at 137.6 ppm and the cyclopropane carbon C-1 (originally C-6 of mesomeric betaine **3c**) bearing a hydrogen atom. In all four cases, **37a–d**, cycloaddition of diphenylcyclopropenone was highly stereoselective, affording only one diastereoisomer.

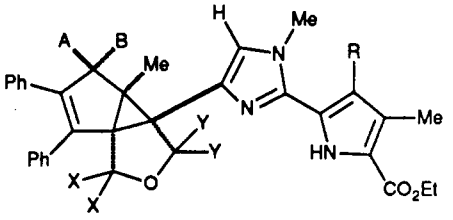


38

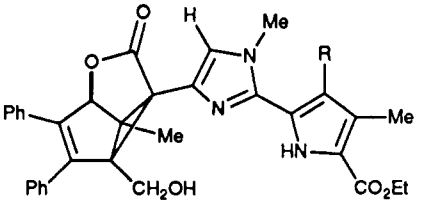
The results of the following chemical transforations performed on **37a** further confirmed the proposed bicyclo[3.1.0]hex-3-en-2-one structure and also established the stereochemistry at C-6. Bicyclo[3.1.0]hex-3-en-2-one **37a** was smoothly reduced with sodium cyanoborohydride in methanol at 0 °C to afford the corresponding allylic alcohol **39a** in 81% yield as a single stereoisomer. The ^{13}C NMR spectrum of doubly labeled **39a** is fully consistent with the assigned bicyclo[3.1.0]hex-3-en-2-ol structure **39a**. Due to the considerable steric hindrance to the hydride approach from the cyclopropane face of the carbonyl group that is blocked by the *endo*-imidazolopyrrole substituent at C-6, the configuration of the hydroxy group in **39b** was assigned as endo. Similarly, treatment of **37a** with 2 equiv of methyllithium in ether–THF at 0 °C afforded as a single product tertiary alcohol **39b**. The endo stereochemistry of imidazolopyrrole rings at C-6 in **37a** was determined on the following basis. In comparing the ^{1}H NMR data for **37a** and **39a**, the imidazole proton is shielded in **37a** due to the cyclopentenone carbonyl group. Reduction of **37a** with excess DIBAL in methylene chloride at 0 °C afforded two lactones **40a** and **40b**. The IR spectra of both compounds **40a,b** displayed characteristic γ-lactone C=O absorptions, 1764 and 1763 cm^{-1}, respectively. Two carbonyl resonances in ^{13}C NMR spectrum of **40a** at 160.2 and 163.1 ppm indicate that both ester groups of the pyrrole ring remained intact during the reduction. The structures **40a,b** also readily accommodate respective ^{13}C NMR lactone carbonyl resonances at 175.3 and 175.6 ppm. In order to unequivocally distinguish between isomeric lactone structures **40a,b** and **41a,b**, respectively, **40a,b** were oxidized with MnO_2 in methylene chloride. Lactone **40a** gave rise to bicyclo[3.1.0]hex-3-en-2-one **40c** (^{13}C NMR C=O cyclopentenone absorption at 199.7 ppm), whereas lactone **40b** provided two compounds: bicyclo[3.1.0]hex-3-en-2-one **40d** (^{13}C NMR C=O cyclopentenone absorption at 199.6 ppm) and bicyclo[3.1.0]hex-3-en-2-ol **40e**. Finally, distinction between the regioisomeric lactone structures **40e** and **40f** was made on the basis of NOE experiments performed on aldehyde **40e**. Irradiation of the AB lactone hydrogen at 4.69 ppm produced 12% NOE enhancement on two ortho-β-phenyl hydrogens at 6.95 ppm,[17] thus establishing that the CO_2Et-cyclopropyl group was reduced to a CH_2-lactone group.



39a R=H
39b R=Me



40a A=OH; B=H; X=H; Y=O; R=CO_2Bn
40b A=OH; B=H; X=H; Y=O; R=CH_2OH
40c A=O; B=O; X=H; Y=O; R=CO_2Bn
40d A=O; B=O; X=H; Y=O; R=CH_2OH
40e A=OH; B=H; X=H; Y=O; R=CHO
40f A=OH; B=H; X=O; Y=H; R=CHO



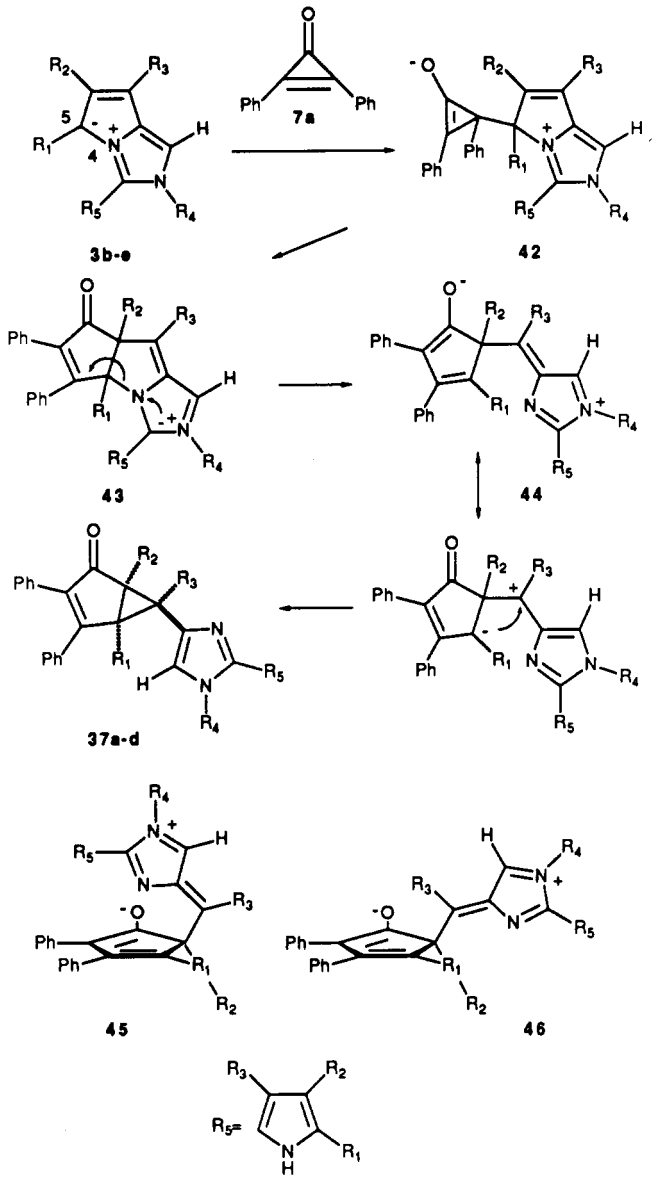
41a R=CO_2Bn
41b R=CH_2OH

The proposed mechanistic pathway involved in the formation of bicyclo[3.1.0]hex-3-en-2-ones **37a–d** is sum-

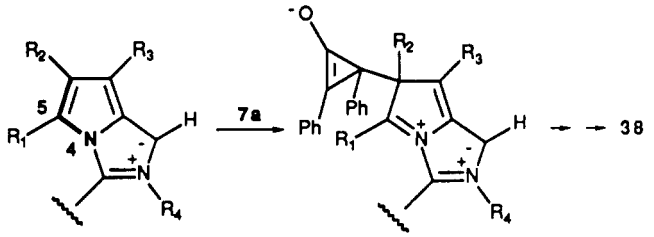
(16) An average three-bond coupling of 4–4.5 Hz is expected for alkyl groups with free rotations, whereas $^4J_{CH}$ are <2 Hz. Breitmaier, E.; Voelter, W. In *Carbon-13 NMR Spectroscopy*; VCH: New York, 1987; pp 140–147.

(17) Dreiding models demonstrate the proximity of lactone endo-H to ortho-β-phenyl hydrogens.

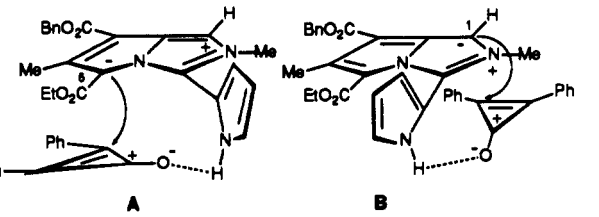
Scheme VIII



Scheme IX



Scheme X



marized in Scheme VIII. Here, in the first step, nucleophilic attack on diphenylcyclopropenone occurred through C-5 of mesomeric betaine **3b–e** to afford intermediate **42**. Rearrangement of **42** to tricyclic ylidic species **43** followed by cleavage of the 4,5-bond in **43** would provide a resonance-stabilized intermediate zwitterion **44**. Cyclization in **44** with concomitant cyclopropane ring formation would give rise to bicyclo[3.1.0]hex-3-en-2-ones **37a–d**. During the cyclopropane ring closure, two conformations can be envisioned: **45** and **46**. Although inspection of Dreiding models indicated that both conformations were strain free, cyclization from the conformation **45** that would lead to endo orientation of imidazole–pyrrole rings was due to the Coulombic interaction between the charges, energetically much more favorable than the cyclization from the conformation **46**, which would give *endo*-alkoxycarbonyl- or *endo*-acetyl-substituted bicyclo[3.1.0]hex-3-en-2-ones. Interestingly, the N_4-C_5-C_6 portion of the mesomeric betaines **3b–e** can be regarded as an isolated enamine functionality. Accordingly, one might expect that the cycloaddition of **7a** to **3b–e** should follow one of the well-established enamine + cyclopropenone reactivity pathways[18] that would lead to disproved structures **38** (Scheme IX). Clearly, this route would not be favored since it involves a highly charged intermediate **47**.

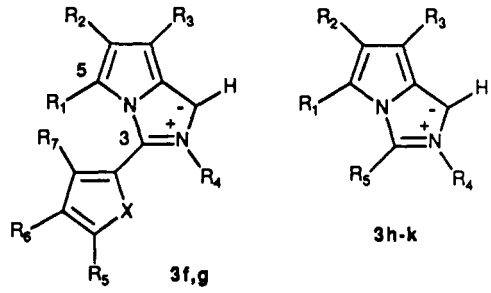
In summary, we have established two major cycloaddition pathways of pyrrolo[1,2-c]imidazole mesomeric betaines **3a–e** with diphenylcyclopropenone and -thione. The behavior of **3a-e** as 1,3-azomethine ylide dipoles **3A** have been considered, so far, only in theory.[1] The isolation of bicyclo[3.1.0]hex-3-en-2-ones **37a–d**, however, clearly demonstrated reactivity of this dipolar form through C-5 of mesomeric betaines **3b–e**. Several hypothesis can be advanced to explain the difference in the reaction pathways of diphenylcyclopropenone cycloadditions to **37a** and **37b–e**: (i) a steric factor, which is related to greater bulkiness of phenyl versus pyrrole group; (ii) an electronic factor, that is reflected by a greater contribution of the dipolar form **48** stabilized through intramolecular hydrogen

(18) (a) Steinfels, M. A.; Dreiding, A. S. *Helv. Chim. Acta* **1972**, *55*, 702. (b) Bilinski, V.; Steinfels, M. A.; Dreiding, A. S. *Ibid.* **1972**, *55*, 1075. (c) Bilinski, V.; Dreiding, A. S. *Ibid.* **1972**, *55*, 1271. (d) Steinfels, M. A.; Drapf, H. W.; Riedl, P.; Sauer, J.; Dreiding, A. S. *Ibid.* **1972**, *55*, 1759. (e) Rosen, M. H.; Fengler, I.; Bonet, G. *Tetrahedron Lett.* **1973**, 949.

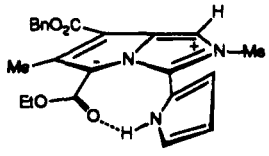
(19) Pyrrolo[1,2-c]imidazole mesomeric betaine **3c** was prepared according to the procedure for preparation of **3b**,[1] by condensing 5-(ethoxycarbonyl)-3-(benzyloxycarbonyl)-2-formylpyrrole[20] with methylamine in methanol: ^{1}H NMR (500 MHz, benzene-d_6) δ 0.85 (3 H, t, J = 7.1 Hz), 0.99 (3 H, t, J = 7.1 Hz), 2.81 (3 H, s), 3.80–3.86 (2 H, m), 3.97–4.07 (2 H, m), 4.79 (1 H, d, J = 12.3 Hz), 4.84 (1 H, d, J = 12.3 Hz), 5.36 (1 H, br, d, J = 11.3 Hz), 5.45 (1 H, br d, J = 11.3 Hz), 6.49 (1 H, s), 6.83 (2 H, dd, J = 1.9, 7.9 Hz), 6.95–7.01 (3 H, m), 7.09 (1 H, t, J = 7.4 Hz), 7.17 (2 H, t, J = 7.4 Hz), 7.44 (2 H, d, J = 7.3 Hz), 7.82 (1 H d, J = 1.3 Hz), 7.91 (1 H, 5), 11.87 (1 H, br s); ^{13}C NMR (125 MHz, benzene-d_6) δ 14.17 (q), 14.49 (q), 34.82 (q), 59.50 (t), 60.98 (t), 65.66 (t), 66.15 (t), 93.19 (s), 104.85 (d), 109.42 (s), 116.73 (d), 117.17 (s), 121.27 (s), 123.84 (s), 125.61 (s), 128.04 (d), 128.17 (d), 128.30 (d), 128.45 (d), 128.56 (d), 128.73 (d), 136.11 (s), 136.40 (s), 137.89 (s), 160.11 (s), 160.81 (s), 162.78 (s), 164.69 (s).

(20) 5-(Ethoxycarbonyl)-3-(benzyloxycarbonyl)-2-formylpyrrole was prepared by the following transformations: acetoxylation of ethyl 4-(benzyloxycarbonyl)-5-methylpyrrole-2-carboxylate[21] with lead tetraacetate–lead dioxide (1:0.89:0.71 molar ratio, respectively) in AcOH at 80 °C for 10 h afforded ethyl 4-(benzyloxycarbonyl)-5-(acetoxymethyl)-pyrrole-2-carboxylate. Hydrolysis of 5-acetoxypyrrole with K_2CO_3 in dioxane–H_2O (2:1) for 14 h at 0 °C and 5 h at room temperature gave the corresponding alcohol. Oxidation of ethyl 4-(benzyloxycarbonyl)-5-(hydroxymethyl)pyrrole-2-carboxylate with MnO_2 in CH_2Cl_2 provided 5-(ethoxycarbonyl)-3-(benzyloxycarbonyl)-2-formylpyrrole: mp 113.5–114.5 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.38 (3 H, t, J = 7.1 Hz), 4.40 (2 H, q, J = 7.1 Hz), 5.36 (2 H, s), 7.33–7.44 (5 H, m), 10.32 (1 H, s), 10.58 (1 H, br s); ^{13}C NMR (75 MHz, $CDCl_3$) δ 14.16 (q), 61.66 (t), 66.74 (t), 117.36 (d), 121.91 (s), 126.71 (s), 128.25 (d), 128.39 (d), 128.61 (d), 134.39 (s), 135.47 (s), 159.81 (s), 162.59 (s), 182.06 (d). Anal. Calcd for $C_{16}H_{15}NO_5$: C, 63.78; H, 5.02; N, 4.65. Found: C, 63.74; H, 5.32; N, 4.50.

(21) Roomi, M. W.; MacDonald, S. F. *Can. J. Chem.* **1970**, *48*, 1689.



3f R_1=R_3=COOEt; R_2=R_4=R_5=Me; R_6=R_7=H; X=O
3g R_1=R_5=CN; R_2=R_6=Et; R_3=R_7=COOBn; R_4=Me; X=NH
3h R_1=CN; R_2=Et; R_3=COOBn; R_4=Me; R_5=Ph; X=NH
3i R_1=R_3=COOEt; R_2=Me; R_4=Pr; R_5=Ph; X=NH
3j R_1=COOEt; R_2=Me; R_3=COMe; R_4=Ph-CH-Me; R_5=Ph; X=NH
3k R_1=R_3=COOEt; R_2=Me; R_4=*c*-C_6H_{11}; R_5=*o*-MeO-C_6H_4; X=NH



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bonding; (iii) a hydrogen bond between the pyrrole N-H and the C=O of diphenylcyclopropenone might effect the orientation of the electrophile during the reaction (Scheme X; the substituents on the pyrrole ring were omitted for clarity). Both orientations of diphenylcyclopropenone A and B are sterically equivalent, however repulsion between positive charges disfavors approach B. We attempted to address these possibilities by preparing the mesomeric betaines **3f–k**, using the general method for the synthesis of pyrrolo[1,2-*c*]imidazole mesomeric betaines, and testing their reactivity to **7a**. In the case of **3f**, the possibility of hydrogen bonding was eliminated, unfortunately **3f** did not react with **7a**. For the mesomeric betaines **3g,h** we hoped that the cyano group at C-5 might effect the negative charge distribution in the betained and reverse the nucleophilic addition of **3g** and **3h** through C-1 an C-5, respectively. Similarly to **3f**, **3g** was unreactive with **7a**, whereas **3h** afforded a complex mixture of products. The bulkier *N*-alkyl (N-2) substituents in **3i–k** were introduced with a goal of forcing the nucleophilic addition of **3i–k** to occur through C-5. Although mesomeric betaine **3i** did react with **7a** to give only a poor yield (8%) of the expected 2(1*H*)-pyridone, **3j,k** failed to give any yield of bicyclo[3.1.0]hex-3-en-2-ones and afforded only starting mesomeric betaines. All experiments were performed by heating mesomeric betaine at reflux with excess **7a** in benzene for 12 h. Further investigations are underway.

Experimental Section

General. The ^{1}H NMR spectra were recorded at 300 and 500 MHz on Brucker AM-300 and AM-500 spectrometers, respectively. When $CDCl_3$ was used as the solvent, chemical shifts were reported in parts per million (ppm) downfield from tetramethylsilane. When benzene-d_6 was used as the solvent, chemical shifts were reported in reference to benzene (7.15 ppm). The ^{13}C NMR spectra were recorded at 75 and 125 MHz on Brucker AM-300 and AM-500 spectrometers, respectively. Chemical shifts are reported in parts per million with reference to $CDCl_3$ (77.00 ppm) and benzene-d_6 (128.00 ppm). The multiplicity of signals was determined by DEPT experiments. The assignment of the carbons bearing protons was made by selective proton decoupling experiments. The coupling constants J_{CH} were obtained through off-resonance decoupling experiments and coupled spectra. $CDCl_3$ used for NMR spectroscopy was passed through basic alumina before use. The IR spectra were recorded on either a Nicolet 7199 FT-IR spectrometer or a Nicolet IR/42 FT-IR spectrophotometer. The fast atom bombardment (FAB) spectra were recorded on the Kratos MS-50L (gas, xenon; high voltage, 6 keV; matrix, *m*-nitrobenzyl alcohol). The UV–visible spectra were measured on a Perkin-Elmer Model 124 double beam spectrophotometer. Elemental analyses were carried out by the Oneida Research Services, Inc. All melting points are uncorrected. Chromatographic separations were performed on open gravity columns with E. Merck Kieselgel 60 (70–230 mesh). Preparative TLC (PTLC) separations were carried out on E. Merck precoated TLC plates (silica gel 60 F-254, layer thickness 0.5 mm).

5-[3,5-Bis(ethoxycarbonyl)-4-methyl-1*H*-pyrrol-2-yl]-1-methyl-3,4,6-triphenyl-2(1*H*)-pyridone (18a). A solution of mesomeric betaine **3a**[1] (70.8 mg, 0.20 mmol) and diphenylcyclopropenone (206.0 mg, 1.00 mmol) in benzene (10 mL) was heated at reflux for 7 h. The solvent was evaporated, and the residue was purified by column chromatography (hexanes–EtOAc, 6:1, 4:1) to afford **18a** (61.9 mg, 55%) as a pale yellow oil. Trituration of the oil with hexanes–EtOAc, 4:1, and recrystallization of the precipitate from the same solvent mixture afforded **18a** as colorless crystals: mp 235–236 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.27 (3 H, t, J = 7.1 Hz), 1.28 (3 H, t, J = 7.1 Hz), 2.21 (3 H, s), 3.37 (3 H, s), 4.15 (2 H, q, J = 7.1 Hz), 4.17 (2 H, q, J = 7.1 Hz), 6.83–6.95 (5 H, m), 7.09–7.32 (10 H, m), 9.22 (1 H, br s); IR (neat) 3277, 2982, 1696, 1662, 1640, 1601, 1508, 1444, 1378, 1302, 1256, 1194, 1069, 751, 699 cm^{-1}; MS (FAB) *m/e* (relative intensity) 561 [(M + H)$^+$, 100], 560 (M$^+$, 59), 515 (49), 154 (17), 118 (71), 105 (25); UV (MeOH) λ_{max} (log ϵ) 208 (4.50), 223 sh (4.33), 265 (4.09), 328 (3.84). Anal. Calcd for $C_{35}H_{32}N_2O_5$: C, 74.98; H, 5.75; N, 5.00. Found: C, 74.58; H, 5.82; N, 4.95.

5-[3,5-Bis(ethoxycarbonyl)-4-methyl-1*H*-pyrrol-2-yl]-1-methyl-3,4,6-triphenyl-2(1*H*)-pyridinethione (18b). A solution of mesomeric betaine **3a** (141.6 mg, 0.40 mmol) and diphenylcyclopropenethione (177.6 mg, 0.80 mmol) in benzene (10 mL) was heated at reflux for 2 h. The solvent was evaporated, and the residue was triturated with hexanes–EtOAc, 3:1. The precipitate was recrystallized from hexanes–EtOAc, 3:1, to afford **18b** (191.2 mg, 83%) as yellow crystals: mp 250–251 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.30 (3 H, t, J = 7.1 Hz), 1.30 (3 H, t, J = 7.1 Hz), 2.20 (3 H, s), 3.88 (3 H, s), 4.13 (2 H, q, J = 7.1 Hz), 4.19 (2 H, q, J = 7.1 Hz), 6.76 (1 H, br d), 6.83 (1 H, br d), 6.89–6.92 (4 H, m), 7.11–7.13 (2 H, m), 7.20–7.23 (4 H, m), 7.31–7.36 (3 H, m), 9.59 (1 H, br s); ^{13}C NMR (125 MHz, $CDCl_3$) δ 11.49 (q), 14.31 (q), 14.35 (q), 44.64 (q), 59.54 (t), 60.65 (t), 116.73 (s), 119.13 (s), 119.60 (s), 126.72 (d), 126.90 (d), 126.99 (d), 127.21 (d), 127.64 (d), 127.68 (d), 127.97 (d), 128.02 (d), 128.06 (d), 128.56 (d), 128.61 (d), 128.96 (d), 129.42 (d), 129.45 (s), 130.52 (d), 134.35 (s), 134.99 (s), 136.90 (s), 139.74 (s), 143.00 (s), 146.45 (s), 150.43 (s), 162.00 (s), 162.00 (s), 163.89 (s), 181.75 (s); IR (KBr) 3286, 2956, 2935, 1708, 1659, 1562, 1483, 1376, 1311, 1256, 1204, 1094, 1069 cm^{-1}; MS (FAB) *m/e* (relative intensity) 577 [(M + H)$^+$, 100], 576 (M$^+$, 70), 531 (60), 154 (7), 118 (26); UV (MeOH) λ_{max} (log ϵ) 209 (4.70), 262 (4.37), 303 (4.23), 363 (4.00). Anal. Calcd for $C_{35}H_{32}N_2O_4S$: C, 72.89; H, 5.59; N, 4.86; S, 5.56. Found: C, 72.99; H, 5.65; N, 4.51; S, 5.32.

5,6-Bis[3-(benzyloxycarbonyl)-5-(ethoxycarbonyl)-4-methyl-1*H*-pyrrol-2-yl]-1-methyl-3,4-diphenyl-2(1*H*)-pyridinethione (18c). A solution of mesomeric betaine **3b**[1] (206.7 mg, 0.331 mmol) and diphenylcyclopropenethione (220.2 mg, 0.993 mmol) in benzene (10 mL) was heated at reflux for 4.5 h. The solvent was evaporated, and the residue was separated by column chromatography (hexanes–EtOAc, 10:1, 6:1) to afford **18c** as a yellow oil. Trituration with (hexanes–EtOAc, 3:1)–ether, 1:1, at 0 °C provided a yellow precipitate which was recrystallized from hexanes–EtOAc (3:1) to afford pure **18c** (66.7 mg, 24%) as yellow crystals: mp 118–120 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.30 (3 H, t, J = 7.1 Hz), 1.34 (3 H, t, J = 7.1 Hz), 2.22 (3 H, s), 2.51 (3 H, s), 3.66 (3 H, s), 4.23 (2 H, q, J = 7.1 Hz), 4.29 (2 H, m), 5.06 (1 H, d, J = 12.0 Hz), 5.11 (1 H, d, J = 12.2 Hz), 5.32 (1 H, d, J = 12.2 Hz), 5.41 (1 H, d, J = 12.0 Hz), 6.32 (1 H, br d), 6.59 (1 H, br d), 6.80–6.87 (3 H, m), 6.98 (1 H, d, J = 6.7 Hz), 7.11 (2 H, t, J = 7.2 Hz), 7.16–7.19 (2 H, m), 7.34–7.48 (10 H, m), 8.69 (1 H, br s), 9.44 (1 H, br s); ^{13}C NMR (125 MHz, $CDCl_3$) δ 11.33 (q), 11.46 (q), 14.27 (q), 14.31 (q), 43.16 (q), 60.48 (t), 60.77 (t), 66.34 (t), 66.51 (t), 115.86 (s), 116.16 (s), 119.65 (s), 120.09 (s), 121.25 (s), 126.90 (d), 127.07 (d), 127.56 (d), 127.82 (d), 128.04 (d), 128.50 (d), 128.64 (d), 128.69 (d), 128.95 (d), 129.09 (d), 129.80

(s), 129.84 (s), 129.90 (d), 130.11 (d), 133.13 (s), 135.29 (s), 135.41 (s), 136.01 (s), 139.16 (s), 141.33 (s), 144.18 (s), 145.37 (s), 160.30 (s), 160.72 (s), 163.20 (s), 164.16 (s), 182.14 (s); IR (KBr) 3391, 3248, 2980, 2937, 1723, 1697, 1571, 1454, 1308, 1248, 1211, 1137, 1064 cm^{-1}; MS (FAB) m/e (relative intensity) 848 [$(M + H)^+$, 49], 847 (M^+, 26), 756 (5), 91 (100); UV (MeOH) λ_{max} (log ϵ) 211 (4.90), 262 sh (4.47), 309 (4.25), 380 (3.90). Anal. Calcd for $C_{50}H_{45}N_3O_9S$: C, 70.82; H, 5.35; N, 4.96; S, 3.78. Found: C, 70.94; H, 5.39; N, 5.01; S, 3.52.

5-[3,5-Bis(ethoxycarbonyl)-4-methyl-1*H*-pyrrol-2-yl]-2-(methylthio)-1-methyl-3,4,6-triphenylpyridinium Iodide (27). A solution of **18b** (60 mg, 0.071 mmol) in dry MeOH (3 mL) was stirred with excess MeI overnight at room temperature. Evaporation of the solvent and PTLC purification (6% MeOH–CH_2Cl_2) afforded **27** (45 mg, 64%) as yellow semi solid: ^1H NMR (500 MHz, $CDCl_3$) δ 1.23 (3 H, t, J = 7.1 Hz), 1.36 (3 H, t, J = 7.1 Hz), 2.19 (3 H, s), 2.48 (3 H, s), 4.12 (2 H, q, J = 7.1 Hz), 4.23 (2 H, q, J = 7.1 Hz), 4.27 (3 H, s), 6.72 (1 H, br d), 6.90 (1 H, br s), 6.98–7.00 (2 H, m), 7.17 (1 H, t, J = 7.6 Hz), 7.21–7.24 (3 H, m), 7.28 (1 H, t, J = 7.6 Hz), 7.31 (1 H, t, J = 7.6 Hz), 7.41 (2 H, t, J = 7.5 Hz), 7.47 (2 H, t, J = 7.6 Hz), 8.45 (1 H, d, J = 7.7 Hz), 11.06 (1 H, br s); ^{13}C NMR (125 MHz, $CDCl_3$) δ 11.09 (q), 14.30 (q), 14.48 (q), 20.29 (q), 46.53 (q), 59.67 (t), 60.29 (t), 115.87 (s), 120.55 (s), 126.61 (d), 126.91 (d), 127.45 (d), 127.64 (d), 127.70 (d), 128.14 (d), 128.29 (d), 128.34 (d), 128.42 (d), 128.47 (d), 128.59 (s), 129.13 (d), 129.34 (d), 130.05 (d), 130.73 (d), 130.75 (d), 131.97 (s), 132.13 (s), 134.20 (s), 134.63 (s), 135.49 (s), 146.07 (s), 155.55 (s), 156.43 (s), 158.41 (s), 164.67 (s); IR (neat) 3171, 3059, 2979, 2932, 1716, 1701, 1696, 1560, 1465, 1444, 1307, 1254, 1185, 1070, 750, 700 cm^{-1}; MS (FAB) m/e (relative intensity) 591 [$(M - I)^+$, 100)], 545 (25), 503 (8); HRMS (FAB) m/e $(M - I)^+$ calcd 591.2317, obsd 591.2297.

Bicyclo[3.1.0]hex-3-en-2-one (37a). A solution of mesomeric betaine **3b** (208.3 mg, 0.33 mmol) and diphenylcyclopropenone (103.0 mg, 0.50 mmol) in benzene (20 mL) was heated at reflux for 3.5 h. The solvent was evaporated, and the residue was purified by column chromatography (hexanes–EtOAc, 10:1, 6:1) to afford **37a** (229.8 mg, 83%) as a pale yellow oil. Trituration of oil with hexanes–EtOAc (4:1) and recrystallization of the precipitate from the same solvent mixture afforded **37a** as colorless crystals: mp 142–143 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 0.85 (3 H, t J = 7.1 Hz), 1.33 (3 H, t, J = 7.1 Hz), 1.87 (3 H, s), 2.58 (3 H, s), 2.96 (3 H, s), 3.91 (1 H, qd, J = 7.1, 10.6 Hz), 4.07 (1 H, qd, J = 7.1, 10.6 Hz), 4.24–4.36 (2 H, m), 4.99 (1 H, d, J = 12.4 Hz), 5.03 (1 H, d, J = 12.4 Hz), 5.25 (1 H, d, J = 12.5 Hz), 5.33 (1 H, J = 12.5 Hz), 6.71 (2 H, d, J = 8.4 Hz), 6.80 (1 H, s), 7.03–7.04 (2 H, m) 7.09–7.17 (3 H, m), 7.22–7.34 (9 H, m), 7.38 (2 H, d, J = 6.9 Hz), 7.44 (2 H, dd, J = 1.3, 7.5 Hz), 8.64 (1 H, br s); IR (KBr) 3399, 3367, 2978, 2936, 1742, 1720, 1700, 1444, 1374, 1264, 1243, 1221, 1204, 1106, 1068 cm^{-1}; MS (FAB) m/e (relative intensity) 832 [$(M + H)^+$, 24], 831 (M^+, 7), 207 (16), 149 (10), 91 (100); UV (MeOH) λ_{max} (log ϵ) 208 (4.78), 263 (4.34), 315 (4.05). Anal. Calcd for $C_{50}H_{45}N_3O_9$: C, 72.19; H, 5.45; N, 5.05. Found: C, 72.16; H, 5.48; N, 5.02.

Bicyclo[3.1.0]hex-3-en-2-one (37b). A solution of mesomeric betaine **3c**[19] (89.6 mg, 0.15 mmol) and diphenylcyclopropenone (77.3 mg, 0.375 mmol) in benzene (5 mL) was heated at reflux for 7 h. The solvent was evaporated and the residue was purified by column chromatography (hexanes–EtOAc, 5:1) to afford **37b** (80.9 mg, 67%) as a pale yellow oil: ^1H NMR (300 MHz, $CDCl_3$) δ 0.86 (3 H, t, J = 7.1 Hz), 1.34 (3 H, t, J = 7.1 Hz), 3.21 (3 H, s), 3.71 (1 H, s), 3.90 (1 H, qd, J = 7.2, 10.8 Hz), 4.02 (1 H, qd, J = 7.2, 10.8 Hz), 4.31 (2 H, q, J = 7.1 Hz), 5.10 (1 H, d, J = 12.7 Hz), 5.14 (1 H, d, J = 12.7 Hz), 5.25 (2 H, s), 6.72 (2 H, dd, J = 1.7, 7.8 Hz), 6.97 (1 H, s), 7.08–7.37 (17 H, m), 7.41–7.44 (2 H, m), 9.40 (1 H, br s); ^{13}C NMR (125 MHz, $CDCl_3$) δ 13.50 (q), 14.30 (q), 33.91 (q), 38.31 (s), 46.89 (s), 54.01 (s), 60.80 (t), 61.63 (t), 65.89 (t), 67.78 (t), 116.33 (s), 117.06 (d), 123.91 (s), 124.77 (d), 127.82 (s), 127.98 (d), 128.00 (d), 128.00 (d), 128.09 (d), 128.17 (d), 128.17 (d), 128.19 (d), 128.46 (d), 128.51 (d), 128.97 (d), 129.24 (d), 129.46 (d), 130.94 (s), 132.95 (s), 133.53 (s), 135.42 (s), 135.87 (s), 137.73 (s), 138.53 (s), 159.22 (s), 159.70 (s), 162.57 (s), 166.98 (s), 167.12 (s), 197.78 (s); IR (neat) 3397, 3250, 3143, 3063, 3032, 2981, 2958, 1714, 1593, 1447, 1375, 1343, 1238, 1202, 1169, 1146, 1092, 1060, 1023, 761, 737 cm^{-1}; MS (FAB) m/e (relative intensity) 804 [$(M + H)^+$, 13], 803 (M^+, 6), 758 (4), 712 (4), 91 (100); HRMS (FAB) m/e $(M + H)^+$ calcd 804.2921, obsd 804.2895.

Bicyclo[3.1.0]hex-3-en-2-one (37c). A solution of mesomeric betaine **3d**[1] (150.0 mg, 0.265 mmol) and diphenylcyclopropenone (200.0 mg, 0.971 mmol) in benzene (8 mL) was heated at reflux for 4 h. The solvent was evaporated, and the residue was purified by column chromatography (hexanes–EtOAc, 3:1) to afford **37c** (142.9 mg, 70%) as a pale yellow oil: ^1H NMR (500 MHz, $CDCl_3$) δ 1.76 (3 H, s), 2.08 (3 H, s), 2.48 (3 H, s), 2.58 (3 H, s), 3.21 (3 H, s), 4.93 (1 H, d, J = 12.3 Hz) 5.06 (1 H, d, J = 12.3 Hz), 5.29 (1 H, d, J = 12.3 Hz), 5.36 (1 H, d, J = 12.3 Hz), 6.67 (2 H, dd, J = 1.5, 7.7 Hz), 6.81 (2 H, d, J = 7.2 Hz), 6.82 (1 H, s), 7.08–7.25 (9 H, m), 7.35–7.37 (5 H, m), 7.46 (2 H, dd, J = 1.5, 7.8 Hz), 8.93 (1 H, br s); ^{13}C NMR (75 MHz, $CDCl_3$) δ 8.74 (q), 11.95 (q), 30.04 (q), 30.25 (q), 33.56 (q), 44.49 (s), 48.91 (s), 63.44 (s), 66.21 (t), 67.32 (t), 120.91 (s), 125.65 (d), 126.03 (s), 126.35 (s), 127.90 (d), 128.03 (d), 128.03 (d), 128.08 (d), 128.19 (d), 128.35 (d), 128.63 (d), 128.85 (d), 129.03 (d), 129.08 (d), 129.30 (d), 131.00 (s), 134.25 (s), 134.31 (s), 134.63 (s), 134.88 (s), 135.71 (s), 136.85 (s), 139.27 (s), 160.32 (s), 161.48 (s), 167.16 (s), 194.66 (s), 200.04 (s), 200.98 (s); IR (neat) 3275, 3136, 3062, 3033, 2932, 1713, 1667, 1588, 1446, 1407, 1353, 1240, 1216, 1198, 1152, 1101, 1075, 775, 738 cm^{-1}; MS (FAB) m/e (relative intensity) 772 [$(M + H)^+$, 22], 664 (6), 622 (7), 189 (8), 91 (100); HRMS (FAB) m/e $(M + H)^+$ calcd 772.3022, obsd 772.2996.

Bicyclo[3.1.0]hex-3-en-2-one (37d). A solution of mesomeric betaine **3e**[1] (73.4 mg, 0.110 mmol) and diphenylcyclopropenone (34.3 mg, 0.167 mmol) in benzene (7 mL) was heated at reflux for 6 h. The solvent was evaporated, and the residue was purified by PTLC (hexanes–EtOAc, 2:1) and then 6% MeOH–CH_2Cl_2 to afford **37d** (72.2 mg, 75%) as a colorless oil: ^1H NMR (500 MHz, $CDCl_3$ δ 0.47 (3 H, t, J = 7.2 Hz), 0.69 (2 H, sextet, J = 7.3 Hz), 0.85 (3 H, t, J = 7.1 Hz), 1.00 (2 H, m), 1.31 (3 H, t, J = 7.1 Hz), 1.88 (3 H, s), 2.58 (3 H, s), 3.12–3.25 (2 H, m), 3.91 (1 H, qd, J = 7.1, 10.7 Hz), 4.06 (1 H, J = 7.1, 10.7 Hz) , 4.25 (1 H, qd, J = 7.1, 10.7 Hz), 4.32 (1 H, qd, J = 7.1, 10.7 Hz), 4.95 (1 H, d, J = 12.2 Hz), 4.98 (1 H, d, J = 12.2 Hz), 5.25 (1 H, d, J = 12.5 Hz), 5.32 (1 H, d, J = 12.5 Hz), 6.79 (2 H, dd, J = 1.4, 8.4 Hz), 6.87 (1 H, s) 7.00–7.02 (2 H, m), 7.11 (2 H, t, J = 7.6 Hz), 7.16–7.19 (1 H, m) 7.21–7.34 (9 H, m), 7.36–7.38 (2 H, m), 7.45 (2 H, dd, J = 1.3, 7.6 Hz), 8.64 (1 H, br s), 8.64 (1 h, br s); ^{13}C NMR (125 MHz, $CDCl_3$) δ 9.06 (q), 11.57 (q), 13.08 (q), 13.52 (q), 14.34 (q), 19.27 (t), 32.25 (t), 42.87 (s), 46.53 (t), 48.52 (s), 56.26 (s), 60.29 (t), 61.21 (t), 65.58 (t), 67.17 (t), 115.60 (s), 120.83 (s), 123.24 (d), 127.28 (s), 127.81 (d), 127.89 (d), 127.89 (d), 127.89 (d), 127.99 (d), 128.08 (d), 128.26 (d), 128.34 (d), 128.37 (d), 128.56 (d), 128.98 (d), 129.16 (d), 130.51 (s), 131.06 (s), 133.58 (s), 134.36 (s), 135.54 (s), 135.63 (s), 136.20 (s), 138.17 (s), 159.78 (s), 160.24 (s), 163.29 (s), 166.69 (s), 166.83 (s), 200.30 (s); IR (neat) 3413, 3259, 2960, 2934, 1720, 1455, 1372, 1242, 1105, 1065, 734 cm^{-1}; MS (FAB) m/e (relative intensity) 874 [$(M + H)^+$, 71], 784 (4), 720 (4), 664 (5), 91 (100); HRMS (FAB) m/e $(M + H)^+$ calcd 874.3703, obsd 874.3669.

Reduction of Bicyclo[3.1.0]hex-3-en-2-one (37a) with $NaBH_4$. To a solution of **37a** (70.9 mg, 0.085 mmol) in MeOH (5 mL) was added at 0 °C over 3 h $NaBH_4$ (10.2 mg, 0.268 mmol). The reaction was quenched by addition of saturated $NaHCO_3$ (1 mL) at 0 °C. The solvents were evaporated, and the residue was partitioned between CH_2Cl_2 and water. The organic layer was dried over $MgSO_4$, and then the solvent was evaporated. PTLC purification of the residue (hexanes–EtOAc, 2:1) afforded alcohol **39a** as colorless oil (58 mg, 81%). Trituration with hexanes–EtOAc (4:1) and recrystallization of the precipitate from the same solvent mixture afforded **39a** as colorless crystals: mp 187.5–188.5 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 0.82 (3 H, t, J = 7.1 Hz), 1.31 (3 H, t, J = 7.1 Hz), 1.88 (3 H, s), 2.53 (3 H, s), 3.09 (3 H, s), 3.84 (1 H, qd, J = 7.1, 10.7 Hz), 4.09 (1 H, qd, J = 7.1, 10.7 Hz), 4.17–4.35 (2 H, m), 5.04 (1 H, d, J = 12.2 Hz), 5.14 (1 H, d, J = 12.2 Hz), 5.27 (1 H, d, J = 12.4 Hz), 5.32 (1 H, d, J = 12.4 Hz), 5.40 (1 H, s), 6.71 (2 H, dd, J = 2.2, 7.5 Hz), 7.05–7.17 (9 H, m), 7.25 (1 H, s), 7.28–7.45 (9 H, m), 8.31 (1 H, br s); ^{13}C NMR (125 MHz, $CDCl_3$) δ 11.65 (q), 14.44 (q), 15.64 (q), 33.75 (q), 38.32 (s), 44.86 (s), 50.94 (s), 60.39 (t), 60.70 (t), 65.72 (t), 67.19 (t), 85.64 (d), 116.25 (s), 121.28 (s), 123.88 (d), 125.76 (s), 126.88 (d), 127.50 (d), 127.72 (d), 127.96 (d), 128.12 (d), 128.14 (d), 128.23 (d), 128.27 (d), 128.38 (d), 128.46 (d), 128.56 (d), 128.90 (d), 130.33 (s), 131.73 (s), 134.71 (s), 135.19 (s), 135.70 (s), 135.72 (s), 135.89 (s), 136.87 (s), 142.46 (s), 159.95 (s), 163.24 (s), 168.37 (s), 168.43 (s); IR (KBr)

3378, 3200–2800, 2980, 2934, 1737, 1719, 1704, 1444, 1400, 1321, 1244, 1218, 1141, 1063 cm^{-1}; MS (FAB) m/e (relative intensity) 834 [(M + H)$^+$, 34], 833 (M$^+$, 15), 91 (100); UV (MeOH) λ_{max} (log ϵ) 208 (4.73), 270 (4.36). Anal. Calcd for $C_{50}H_{47}N_3O_9$: C, 72.01; H, 5.68; N, 5.04. Found: C, 71.98; H, 5.75; N, 5.05.

Reaction of Bicyclo[3.1.0]hex-3-en-2-one (37a) with MeLi. To a solution of **37a** (173.3. mg, 0.209 mmol) in ether–THF (1:2, 12 mL) at −78 °C was added a solution of MeLi in ether (312 μL, 1.4 M, 0.437 mmol) over 2 min. After stirring at −78 °C for 30 min, the solution was stirred at 0 °C for 1.5 h. The reaction mixture was then quenched with aqueous buffer (pH = 7) and acetic acid (200 μL). The organic phase was then washed with saturated $NaHCO_3$ and dried over $MgSO_4$. Evaporation of the solvent and PTLC separation of the residue (hexanes–EtOAc, 1:1) afforded alcohol **39b** (44.2 mg, 47%, based on recovered **37a**) and unreacted **37a** (81.1 mg, 47%): ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.91 (3 H, t, J = 7.1 Hz), 1.34 (3 H, t, J = 7.1 Hz), 1.66 (3 H, s), 1.75 (3 H, s), 2.58 (3 H, s), 3.01 (3 H, s), 3.94 (1 H, qd, J = 7.1, 10.7 Hz), 4.10 (1 H, qd, J = 7.1, 10.7 Hz), 4.26–4.33 (2 H, m), 4.87 (1 H, d, J = 12.1 Hz), 5.17 (1 H, d, J = 12.1 Hz), 5.24 (1 H, d, J = 12.4 Hz), 5.30 (1 H, d, J = 12.4 Hz), 6.68 (2 H, d, J = 7.9 Hz), 7.03–7.15 (11 H, m), 7.25–7.29 (3 H, m), 7.36–7.41 (5 H, m), 8.33 (1 H, br s); ^{13}C NMR (125 MHz, $CDCl_3$) δ 10.45 (q), 11.67 (q), 13.84 (q), 14.41 (q), 27.12 (q), 33.75 (q), 41.57 (s), 46.83 (s), 50.06 (s), 60.53 (t), 60.64 (t), 65.74 (t), 67.06 (t), 86.59 (s), 116.19 (s), 121.39 (s), 123.60 (d), 126.83 (d), 126.88 (d), 127.44 (d), 127.60 (d), 127.78 (d), 128.09 (d), 128.18 (d), 128.22 (d), 128.25 (d), 128.41 (d), 128.51 (d), 128.51 (d), 129.45 (s), 130.42 (s), 132.69 (s), 135.16 (s), 135.23 (s), 135.67 (s), 135.78 (s), 135.89 (s), 136.97 (s), 145.87 (s), 160.04 (s), 163.23 (s), 168.48 (s), 168.63 (s); IR (neat) 3500–2800, 3385, 2981, 2934, 1718, 1443, 1400, 1371, 1245, 1213, 1142, 1065, 739 cm^{-1}; MS (FAB) m/e (relative intensity) 848 [(M + H)$^+$, 18], 847 (M$^+$, 8), 830 (7), 804 (6), 758 (4), 333 (14), 91 (100); HRMS (FAB) m/e (M + H)$^+$ calcd 848.3547, obsd 848.3504.

Reduction of Bicyclo[3.1.0]hex-3-en-2-one (37a) with DIBAL. To a solution of **37a** (523.6 mg, 0.630 mmol) in CH_2Cl_2 (25 mL) was added at 0 °C, over 5 min, DIBAL in toluene (2.50 mL, 2.875 mmol). After stirring 45 min at 0 °C, the reaction was quenched by dropwise addition of MeOH–H_2O (3 mL, 1:1). More water was added, and then the organic layer was separated and dried over $MgSO_4$. The solvent was evaporated, and the residue was purified by column chromatography (hexanes–EtOAc, 4:1, 2:1, 1:1) to afford **40a** (R_f 0.66, hexanes–EtOAc, 2:1) and **40b** (R_f 0.41, hexanes–EtOAc, 2:1). Lactone **40b** was purified further by PTLC (R_f 0.52, hexanes–THF, 1.5:1) to afford pure **40a** (25 mg, 6%), whereas lactone **40b** was purified by PTLC (R_f 0.39, 6% MeOH–CH_2Cl_2) to afford pure **40b** (30 mg, 8%). **40a**: ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.31 (3 H, t, J = 7.1 Hz), 1.69 (3 H, s), 2.55 (3 H, s), 3.16 (3 H, s), 4.25–4.30 (2 H, m), 4.37 (1 H, d, J = 10.2 Hz), 4.69 (1 H, d, J = 10.2 Hz), 4.92 (1 H, d, J = 12.0 Hz), 5.17 (1 H, d, J = 12.0 Hz), 5.46 (1 H, s), 6.85 (2 H, d, J = 6.9 Hz), 6.98 (2 H, d, J = 6.9 Hz), 7.04–7.11 (4 H, m), 7.13 (1 H, s), 7.18–7.26 (4 H, m), 7.33–7.38 (3 H, m), 9.00 (1 H, br s); ^{13}C NMR (125 MHz, $CDCl_3$) δ 11.56 (q), 14.06 (q), 14.39 (q), 33.83 (q), 34.11 (s), 41.67 (s), 52.71 (s), 60.60 (t), 64.93 (t), 65.27 (t), 84.18 (d), 116.66 (s), 121.59 (s), 123.42 (d), 125.26 (s), 127.47 (d), 127.62 (d), 127.97 (d), 128.33 (d), 128.44 (d), 128.57 (d), 128.64 (d), 128.87 (d), 129.17 (d), 130.09 (s), 130.45 (s), 132.28 (s), 133.78 (s), 133.98 (s), 135.65 (s), 137.53 (s), 143.06 (s), 160.20 (s), 163.12 (s), 175.28 (s); IR (neat) 3400–2800, 2930, 2853, 1764, 1709, 1445, 1385, 1248, 1149, 1126, 1065, 1001, 721 cm^{-1}; MS (FAB) m/e (relative intensity) 684 [(M + H)$^+$, 78], 666 (7), 638 (9), 620 (12), 154 (61), 91 (100); HRMS (FAB) m/e (M + H)$^+$ calcd 684.2709, obsd 684.2740. **40b**: ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.32 (3 H, t, J = 7.1 Hz), 1.68 (3 H, s), 2.22 (3 H, s), 3.67 (3 H, s), 3.78 (1 H, d, J = 12.1 Hz), 3.94 (1 H, d, J = 12.1 Hz), 4.28 (2 H, q, J = 7.1 Hz), 4.33 (1 H, d, J = 10.3 Hz), 4.64 (1 H, d, J = 10.3 Hz), 5.50 (1 H, s), 6.93 (2 H, dd, J = 1.4, 7.7 Hz), 7.02 (2 H, d, J = 7.0 Hz), 7.11–7.16 (3 H, m), 7.19 (1 H, s), 7.24–7.29 (3 H, m), 9.16 (1 H, br s); ^{13}C NMR (125 MHz, $CDCl_3$) δ 10.12 (q), 14.06 (q), 14.45 (q), 34.23 (s), 34.32 (q), 42.15 (s), 52.95 (s), 54.61 (t), 60.31 (t), 64.95 (t), 83.78 (d), 120.70 (s), 121.08 (s), 123.43 (d), 125.60 (s), 127.44 (d), 127.60 (d), 127.79 (s), 127.99 (d), 128.31 (d), 128.75 (d), 129.32 (d), 130.42 (s), 132.83 (s), 133.51 (s), 133.98 (s), 137.94 (s), 142.01 (s), 161.11 (s), 175.63 (s); IR (neat) 3400–2800, 3281, 2926, 2854, 1763, 1699, 1448, 1385, 1255, 1195, 1125, 1087, 1064, 1024, 721 cm^{-1}; MS (FAB) m/e (relative intensity) 580 [(M + H)$^+$, 100], 562 (18), 545 (21), 498 (11), 154 (36), 91 (15); HRMS (FAB) m/e (M + H)$^+$ calcd 580.2447, obsd 580.2466.

Oxidation of Lactone 40a with MnO_2. Oxidation of **40a** (15 mg, 0.022 mmol) with excess activated MnO_2 in CH_2Cl_2 (3 mL) and PTLC purification of the product (R_f 0.26, hexanes–EtOAc, 1:1) afforded **36c** (12 mg, 80%) as a pale yellow viscous oil: ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.37 (3 H, t, J = 7.1 Hz), 1.67 (3 H, s), 2.61 (3 H, s), 3.04 (3 H, s), 4.35 (2 H, q, J = 7.1 Hz), 4.54 (1 H, d, J = 10.4 Hz), 4.91 (1 H, d, J = 12.2 Hz), 4.93 (1 H, d, J = 10.4 Hz), 5.07 (1 H, d, J = 12.2 Hz), 6.79 (1 H, s), 6.90 (2 H, dd, J = 1.6, 8.3 Hz), 7.07–7.18 (5 H, m), 7.26–7.30 (8 H, m), 9.48 (1 H, br s); ^{13}C NMR (125 MHz, $CDCl_3$) δ 7.71 (q), 11.73 (q), 14.41 (q), 33.55 (q), 37.23 (s), 47.91 (s), 59.07 (s), 60.62 (t), 64.83 (t), 65.69 (t), 116.43 (s), 121.09 (s), 126.44 (d), 127.03 (s), 127.99 (s), 128.08 (d), 128.20 (d), 128.36 (d), 128.39 (d), 128.39 (s), 128.51 (d), 128.71 (d), 129.41 (d), 129.76 (d), 130.04 (s), 130.31 (d), 132.34 (s), 134.86 (s), 135.73 (s), 140.28 (s), 158.54 (s), 160.55 (s), 163.31 (s), 170.73 (s), 199.70 (s); IR (neat) 2980, 1776, 1700, 1446, 1358, 1262, 1246, 1149, 1106, 1067, 734 cm^{-1}; MS (FAB) m/e (relative intensity) 682 [(M + H)$^+$, 100], 636 (16), 528 (7), 154 (71), 91 (50); HRMS (FAB) m/e (M + H)$^+$ calcd 682.2553, obsd 682.2516.

Oxidation of Lactone 40b with MnO_2. Oxidation of **40b** (25 mg, 0.043 mmol) with an excess activated MnO_2 in CH_2Cl_2 (3 mL), and PTLC purification of the product (6% MeOH–CH_2Cl_2) afforded **40d** (R_f 0.42, 7 mg, 28%) as a pale yellow viscous oil and **40e** (R_f 0.57, 14 mg, 56%) as a colorless viscous oil. **40d**: ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.38 (3 H, t, J = 7.1 Hz), 1.65 (3 H, s), 2.32 (3 H, s), 3.57 (3 H, s), 4.31 (1 H, d, J = 12.8 Hz), 4.32–4.38 (2 H, m), 4.40 (1 H, d, J = 12.8 Hz), 4.52 (1 H, d, J = 10.6 Hz), 5.00 (1 H, d, J = 10.6 Hz), 6.75 (2 H, dd, J = 1.4, 8.5 Hz), 6.78 (1 H, s), 7.11–7.14 (2 H, m), 7.17–7.20 (1 H, m), 7.28–7.37 (5 H, m), 9.32 (1 H, br s); ^{13}C NMR (125 MHz, $CDCl_3$) δ 7.57 (q), 10.08 (q), 14.47 (q), 34.21 (q), 36.95 (s), 47.60 (s), 54.50 (t), 58.71 (s), 60.49 (t), 64.88 (t), 120.70 (s), 122.62 (s), 126.56 (d), 127.13 (d), 127.74 (s), 128.12 (s), 128.19 (d), 128.49 (d), 128.88 (d), 129.42 (d), 129.78 (s), 129.88 (d), 130.33 (s), 131.84 (s), 134.36 (s), 140.99 (s), 158.23 (s), 161.58 (s), 170.45 (s), 199.55 (s); IR (neat) 3400–2800, 3293, 2929, 1774, 1700, 1590, 1413, 1357, 1255, 1200, 1119, 1074, 1019, 735 cm^{-1}; MS (FAB) m/e (relative intensity) 578 [(M + H)$^+$, 72], 577 (M$^+$, 39), 560 (100), 514 (64), 472 (17), 154 (72); HRMS (FAB) m/e (M + H)$^+$ calcd 578.2291, obsd 578.2319. **40e**: ^{1}H NMR (500 MHz, $CDCl_3$) δ 1.33 (3 H, t, J = 7.1 Hz), 1.66 (3 H, s), 2.54 (3 H, s), 3.56 (3 H, s), 3.56 (3 H, s), 4.26–4.33 (2 H, m), 4.36 (1 H, d, J = 10.3 Hz), 4.69 (1 H, d, J = 10.3 Hz), 5.44 (1 H, s), 6.78 (2 H, dd, J = 1.4, 7.8 Hz), 6.95 (2 H, dd, J = 2.0, 7.8 Hz), 7.05–7.10 (3 H, m), 7.21–7.25 (3 H, m), 7.34 (1 H, s), 9.30 (1 H, br s), 9.68 (1 H, s); ^{13}C NMR (125 MHz, $CDCl_3$) δ 10.28 (q), 13.98 (q), 14.37 (q), 34.00 (s), 34.29 (q), 41.85 (s), 52.76 (s), 60.84 (t), 65.02 (t), 84.03 (d), 121.94 (s), 123.83 (s), 124.27 (d), 126.58 (s), 127.48 (d), 127.69 (d), 128.00 (d), 128.29 (d), 128.62 (d), 129.15 (d), 129.78 (s), 130.13 (s), 133.40 (s), 133.64 (s), 133.73 (s), 136.52 (s), 142.71 (s), 160.29 (s), 175.52 (s), 185.10 (d); IR (neat) 3400–2800, 3221, 3138, 2980, 2931, 1758, 1713, 1676, 1446, 1379, 1266, 1197, 1089, 1024, 722 cm^{-1}; MS (FAB) m/e (relative intensity) 578 [(M + H)$^+$, 100], 577 (M$^+$, 23), 514 (13), 289 (13), 154 (92); HRMS (FAB) m/e (M + H)$^+$ calcd 578.2291, obsd 578.2324.

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Supplementary Material Available: Completely assigned ^{13}C resonances for **18b,c**, **37b,c**, and **39a**; ^{1}H NMR and ^{13}C NMR spectra of **18a–c**, **27**, **37a–d**, **39a,b**, **40a–e**; ^{13}C NMR spectra of single ^{13}C-enriched samples of **18a,b**; and ^{13}C NMR spectra of doubly ^{13}C-enriched samples of **18a–c**, **37a,b**, **39a** (40 pages). Ordering information is given on any current masthead page.