Reactions and Rearrangements in 2-Oxa[3.2.0]bicycloheptanones[1]

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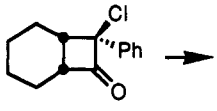
Received March 17, 1992

The furan-fused chlorocyclobutanone **6** undergoes reaction with O, N, S, C nucleophiles at a much slower rate than its pyran homolog, which is attributed to a reluctance to enolization. Instead of substitution products, rearranged products were formed. For instance, 7-membered ring lactones **8** and **9** were derived via vinyl ketenes, while 5-membered ring lactones **12**, **19**, and **20** resulted from opening of the cyclobutanone and/or of the tetrahydrofuran ring. Phenylthiolate behaved exceptionally as a nucleophile, leading, presumably via electron transfer, to ipso substitution and then to a naphthofuran.

α-Halocyclobutanones have proven to be versatile intermediates in the synthesis of γ-lactones,[2] cyclopropanes,[3] cyclopentanones,[4] pyrrolidones,[5] and tropolones.[6] Recently, we have shown that α-chlorocyclobutanones fused to a cyclohexane ring (cf. **1**) underwent cine substitution with O, S, N, and even C nucleophiles to produce **3** under mild conditions (room temperature).[7] These transformations were postulated to proceed via oxyallyl cation intermediates **2**, the formation of which depends on enolization of the cyclobutanone toward the ring junction of the bicyclooctanone (see **1a**). Such enolizations, which introduce a double bond at the ring junction, might be expected to be retarded in a bicyclo[3.2.0]heptanone system. Indeed, we have reported[7b] that **4a**, the cyclopentane-fused analog of **1**, was unreactive toward sodium acetate in refluxing HOAc, yet **4c** had been converted to tropolone on reflux with NaOAc in HOAc (via cine substitution),[6] indicating the sensitivity of this system to structural features.



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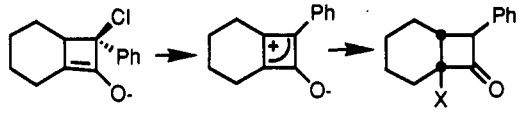
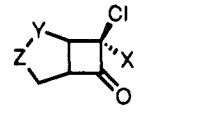
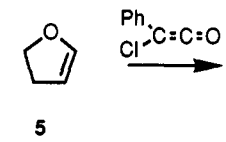


1a **2** **3**

Recently,[8] we established that oxabicyclo[4.2.0]octanone **4d**, the oxa analog of **1**, underwent reaction with nucleophiles at room temperature and at an accelerated rate compared to **1**. Due to the presence of the ether function,



4a, Z-Y=CH_2CH_2, X=Ph
b, Z-Y=CH=CH, X=Ph
c, Z-Y=CH=CH, X=Cl
d, Z-Y=CH_2CH_2O, X=Ph



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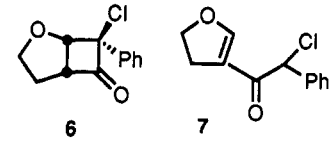

6 **7**

the products suffered interesting transformations, such as ring opening to a cyclobutenone.[8] This prompted us to study the oxabicyclo[3.2.0]heptanone system **6** in order to examine further the role of oxygen in these bicyclic systems and to learn about the scope of the above-mentioned transformations.

Bicyclo[3.2.0]heptanone **6** was prepared in 75% yield by cycloaddition of phenylchloroketene to 4,5-dihydrofuran (**5**). The product was accompanied by 15% of the ring-opened form **7**. The structure of **7** was apparent from the vinylic triplet (J = 1.5 Hz) at 7.44 ppm and the side-chain singlet protons at 5.30 ppm, as well as from the correlated ^{13}C absorptions which showed an α,β-unsaturated carbonyl at 187.0 ppm and two sp^2 carbons at 159.5 (C-1) and 117.1 (C-5). The formation of **7** was surprising since we had shown that the silyl enol ether of cyclopentanone underwent clean cycloaddition to dichloroketene yielding only a fused cyclobutanone.[9] Since **6** did not convert to **7** under the reaction conditions, the cycloaddition in the case of dihydrofuran probably proceeded in part via a stepwise mechanism in which an intermediate carbocation is stabilized by the ether oxygen.

Unlike its homolog **4d**, chloro ketone **6** did not react at room temperature with many O or N (NaOAc, NaOH, NaN_3) nucleophiles but required more drastic conditions that produced changes in the bicyclic skeleton. For instance, heating **6** with sodium acetate in refluxing acetonitrile for 30 h produced the seven-membered ring lactone **8a** and its isomer **9a** as an unseparable mixture in 45% yield. We found that heating of this mixture with TEA in acetonitrile caused complete isomerization to the conjugated lactone **9a**. The structure of **8a** and **9a** was indicated by HRMS and by NMR. Lactone **8a** showed a vinylic doublet at 5.58 ppm and ^{13}C signals at 113.1 (C-1) and 149.7 (C-5) ppm.[10] Lactone **9a** showed characteristic conjugated ester signals at 6.63 ppm for a vinylic hydrogen

(1) Synthetic Methods 39. For paper 38 see: Hassner, A.; Fischer, B. *Tetrahedron Lett.* **1990**, *31*, 7213.
(2) (a) Ali, S. M.; Roberts, S. M. *J. Chem. Soc., Perkin Trans. 1*, **1976**, 1934. (b) Hassner, A.; Pinnick, H. W.; Ansell, J. M. *J. Org. Chem.* **1978**, *43*, 1774.
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(4) (a) Bartlett, P. D.; Ando, T. *J. Am. Chem. Soc.* **1970**, *92*, 7518. (b) Greene, A. E.; Lansard, J. P.; Luhe, J. L.; Petrier, C. *J. Org. Chem.* **1984**, *49*, 931. (c) Paquette, L. A.; Valpey, R. S.; Annis, G. D. *J. Org. Chem.* **1984**, *49*, 1317.
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(6) (a) Stevens, H. C.; Reich, D. A.; Brandt, D. R.; Fountain, K. R.; Gaughan, E. J. *J. Am. Chem. Soc.* **1965**, *87*, 5257. (b) Tsunetsugu, J.; Sato, M.; Kanda, M.; Lakahashi, M.; Ebine, S. *Chem. Lett.* **1977**, 885.
(7) (a) Hassner, A.; Naidorf-Meir, S.; Gottlieb, H. E. *Tetrahedron Lett.* **1990**, *31*, 2181. (b) Hassner, A.; Dillon, J.; Onan, K. D. *J. Org. Chem.* **1986**, *51*, 3315. (c) Hassner, A., Naidorf-Meir, S. *J. Org. Chem.* **1989**, *54*, 4954.
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(9) Krepski, L. R.; Hassner, A. *J. Org. Chem.* **1978**, *43*, 3173.
(10) HRMS and IR spectra were taken on the mixture of **8a** and **9a**.

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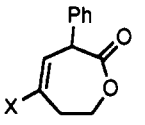
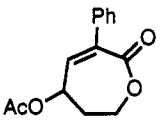
and at 113.0 ppm for the β carbon.

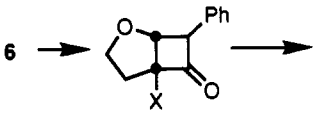


8a, X=OAc
8b, X=OMe

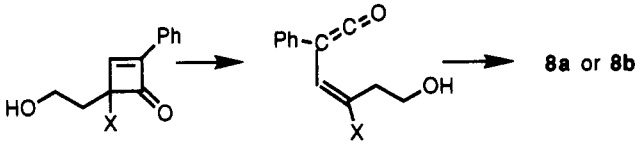


9a, X=OAc
9b, X=OMe

With the stronger base NaOMe, **6** did react at room temperature to produce the unstable cyclobutenone **11b** in quantitative yield, presumably via initial formation of the cine substitution product **10b**. When **11b** was heated in benzene it rearranged to lactone **8b**. This transformation most likely involves electrocyclic opening of the cyclobutenone ring to a vinylketene,[7] which is trapped intramolecularly by the alcohol. This explains the formation of **8b** rather than of its conjugated isomer **9b** and also explains the formation of **8a** and **9a** on heating with NaOAc. Again the structures of **11** and **8b** were apparent from NMR and HRMS.

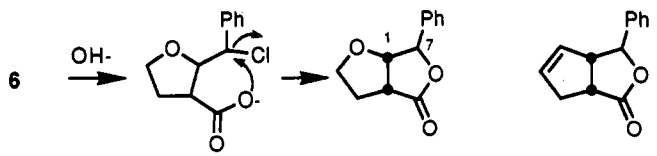


10a,X=OAc
10b,X=OMe



11a,X=OAc
11b, X=OMe

Chloro ketone **6** was unreactive toward TEA in CH_3C-N-H_2O at room temperature, conditions under which the six-membered ring homolog **4d** reacted within minutes to form dimeric products.[11] By following the reaction in D_2O by means of ^1H NMR, we verified that no D-exchange had taken place in **6** and therefore no reversible enolization had occurred. When the mixture was refluxed for 7 h with NaOH, lactone **12** was isolated in 65% yield, as a 1:2 cis–trans mixture, which was separated by chromatography. Lactone **12** showed characteristic ester peaks at 178.1 in the ^{13}C NMR and at 1766 cm^{-1} in the IR. In the ^1H NMR **12a** showed a doublet at 5.58 ppm (J = 4 Hz) for the proton next to the lactone O and at 4.73 ppm for H-1. In the trans (H1–H7) isomer **12b** the two hydrogens appeared as singlets at 5.55 (H-7) and at 4.54 (H-1) (see ref 17). Most likely, attack of HO^- on the cyclobutanone carbonyl of **6** had led to ring opening and lactonization (see **13**). In fact,

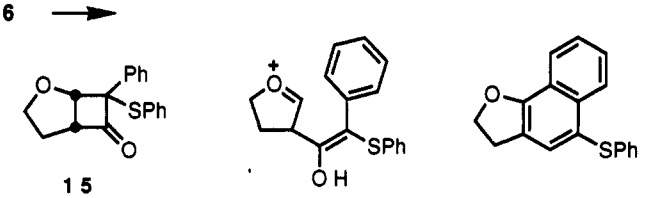


13 **12a**,Ph cis **14**
b, Ph trans

we observed the same phenomenon in the reaction of **4b** with NaOH, which produced lactone **14**. The latter showed similar absorption to **12** and characteristic peaks for the C=C. In these systems, because of unfavorable enolization toward the ring junction, HO^- had attacked at the C=O function.

Unexpectedly, the reaction of **6** with KSPh at room temperature led to **15** as the sole product (stereochemistry undetermined) in 55% yield. This is the *first example in the reaction of fused chlorocyclobutanones with nucleophiles in which ipso rather than cine substitution was observed.* The structure of **15** was deduced from its ^1H and ^{13}C NMR spectra which showed absorptions similar to **6**.

We believe that, in the absence of enolization or ring opening,[12] electron transfer from the phenyl thiolate to chloro ketone **6** may take place to produce a radical anion. The latter would expel Cl– and lead to **15** by radical combination. Indeed, when the reaction was attempted in the presence of 1,4-dinitrobenzene, a free-radical inhibitor, no reaction occurred. Likewise, no reaction was observed when **6** was treated with the less basic PhSH–TEA. Russell et al. had observed that α-halo ketones can undergo electron-transfer reactions with some nucleophiles,[13] including PhS^-.



15 **17** **16**

The sulfide **15** was transformed to naphthofuran **16** in 65% yield by refluxing in $CHCl_3$ in the presence of *p*-TsOH. This reaction is analogous to one described for similar 2-arylcyclobutanones[14] and probably proceeds via the ring-opened intermediate **17**, followed by ring closure and elimination of water.

Diethyl potassiomalonate reacted with **6** at 20 °C to produce the cine substitution product as a cis–trans isomer mixture (**18a** and **18b**) in 30% yield together with the unusual product **18c** (25%). The regiochemistry of the products was evident from the singlet of the ring junction proton in **18c**, H-1 at 5.20 ppm, and the characteristic two doublets at 5.37 and 5.07 (J = 7.5 Hz) and 5.22 and 4.44 ppm (J = 5 Hz) for **18a** and **18b**, respectively, as well as from ^{13}C NMR, two quarternary carbons at 76.9 and 72.0 for **18c**, and one quarternary carbon at 72.2 and 70.1 for **18a** and **18b**, respectively. Though the origin of **18c** is still not certain, it may involve nucleophilic attack of the malonate anion on the Cl of **6** to produce diethyl chloromalonate which later acts as a chlorinating species. In an analogous transformation $ClCH_2NO_2$ was one of the products of reaction of CH_3NO_2 with α-chloroacetophenone.[13]

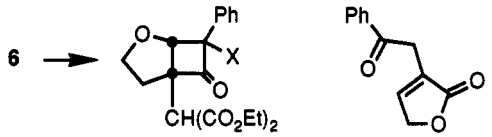
Finally, we examined the reaction of **6** with azide ion in order to compare it with the reaction of **4d**, which had led to an interesting hemiketal that contained a phenyltriazole unit; it had been postulated that phenyltriazole **21** was generated in the reaction but it could only be trapped and not isolated.[8] Refluxing of **6** with NaN_3 in acetone led to

(11) Hassner, A.; Naidorf-Meir, S.; Gottlieb, H. E.; Goldberg, I. *J. Org. Chem.* **1992**, *57*, 2442.

(12) It is possible that the first step is base-catalyzed enolization with opening of the furan ring and formation of the allylic isomer of **11** (X = Cl), which undergoes a substitution at either end of the allylic system to produce compounds of type **10** or **15**. However, this is less likely because of the apparent difficulty of obtaining the required enolate.

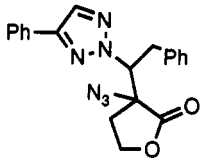
(13) Russell, G. A.; Ras, F. *J. Am. Chem. Soc.* **1985**, *107*, 2506.

(14) Duperrouzel, P.; Lee Ruff, E. *Can. J. Chem.* **1980**, *58*, 51.



18a, X=βH
b, X=αH
c, X=Cl

19



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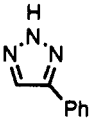

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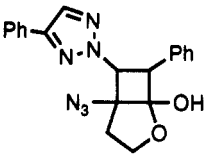
Scheme I



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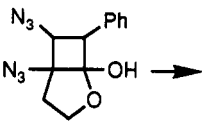

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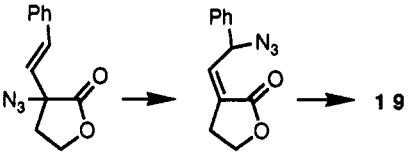

24 25 19

isolation of phenyltriazole **21** in 30% yield, as well as the unusual products of **19** and **20**. The structures of **19** and **20** were verified by ^{13}C and ^{1}H correlated spectra, IR and MS. A plausible explanation for the formation of the products is given in Scheme I. Apparently, phenyltriazole competes with azide ion in the Michael addition to the primary product **11** (X = N_3) and the hemiketal **22** then opens to lactone **20**. A similar sequence most likely leads from **23** to **24** with elimination of azide ion. This is followed by an allylic azide migration[15] from **24** to **25** and hydrolysis of the benzylic azide to a ketone[16] with exo to endocyclic double-bond migration to produce **19**.

In conclusion, the chlorooxabicyclo[3.2.0]heptanone **6** was prepared, and its behavior toward several nucleophiles was examined. Enolization toward the ring junction in the oxabicycloheptanone **6** is greatly retarded compared to the oxabicyclooctanone **4d** and proceeds only with strong nucleophiles (MeO^-, $^-CH(COOEt)_2$ at 20 °C or with N_3^- on heating). The cine substitution products were not isolated but underwent further transformations; with oxygen nucleophiles such as AcO^- or HO^- (from TEA – water), where heating was required, the products were seven- or five-membered-ring lactones. These were formed either via vinylketenes or by opening of the cyclobutanone and/or the tetrahydrofuran ring. PhS^- gave an ipso substitution product (presumably via electron transfer) that underwent acid-catalyzed rearrangement to a naphthofuran.

Experimental Section[17]

7-Chloro-7-phenyl-2-oxabicyclo[3.2.0]heptan-6-one (6) and 3-(2-Chlorophenacyl)-4,5-dihydropyran (7). To a dry three-necked flask under argon equipped with a reflux condenser and an addition funnel were added 5 mL of dihydropyran in 25 mL of dry THF and 5 g (0.026 mol) of 2-chloro-2-phenylacetyl chloride. To this refluxing mixture was added a solution of 0.026 mol of TEA in 10 mL THF over a period of 0.5 h. The mixture was stirred for an additional hour, and the $Et_3NH^+Cl^-$ was removed by filtration. The filtrate was evaporated, and 50 mL of ether was added to the residue. The ethereal solution was washed successively with 5% HCl, 10% $NaHCO_3$, and saturated NaCl and dried ($MgSO_4$). Removal of the solvent in vacuum gave an oil which was purified by chromatography on silica gel (EtOAC–hexane (1.9)) to give 4.4 g of **6** (75%) as an oil together with 0.6 g (10%) of **7**, mp 90 °C, recrystallized from CH_2Cl_2-petroleum ether. **6**: ^1H NMR ($CDCl_3$) δ 7.57 (m, 2 H), 7.38 (m, 3 H), 5.08 (d, J = 6 Hz, H-1), 4.35 (dddt, J = 9.5, 6, 1.5, 0.5 Hz, H-5), 3.95 (ddd, J = 10, 8, 2 Hz, H-3 eq), 3.40 (dddt, J = 11, 9.6, 0.5 Hz, H-3 ax), 2.27 (ddddd, J = 13, 7, 4.5, 2, 0.5 Hz, H-4 eq), 2.04 (dddd, J = 13, 10.5, 9, 8 Hz, H-4 ax); ^{13}C NMR ($CDCl_3$) δ 203.5 (C-6), 133.2, 129.2, 128.7, 126.2, 82.1 (C-1), 78.1 (C-7), 69.7 (C-3), 62.6 (C-5), 28.6 (C-4); IR (neat) 1780, 1485, 1442 cm^{-1}; MS (NH_3) m/z 240 (M + NH_4^+), 223 (M + 1), 206 (M – Cl + H). Anal. Calcd for $C_{12}H_{11}ClO_2$: C, 64.85; H, 4.99. Found: C, 64.38; H, 5.13.

7: ^1H NMR ($CDCl_3$) δ 7.45 (m, 2 H), 7.42 (t, J = 1.5 Hz, H-1), 7.33 (m, 3 H), 5.70 (s, H-7), 4.51 (m, H-3), 2.85 (m, H-4); ^{13}C NMR ($CDCl_3$) δ 187.1 (C-6), 159.5 (C-1), 136.5, 128.8, 127.9, 117.1 (C-5), 62.6 (C-3), 27.6 (C-4); IR (neat) 3055, 1632, 1538 cm^{-1}; MS (EI) m/z 222 (M^+), 187 (M^+ – Cl), 159 (M^+ – CO). Anal. Calcd for $C_{12}H_{11}ClO_2$ C, 64.85; H, 4.99. Found: C, 64.55; H, 4.85.

Reaction of 6 with Nucleophiles. General Procedure. A mixture of 0.2 g (0.9 mmol) of **6** in 20 mL of a dry solvent and 1–3 equiv of the nucleophile was refluxed under argon for 7–30 h. The solvent was removed in vacuum, and the resulting oil was dissolved in CH_2Cl_2, washed with saturated NaCl, and dried over $MgSO_4$. Removal of the solvent gave an oil which was purified by chromatography.

Reaction of 6 with Sodium Acetate. The reaction was carried out with 3 equiv of NaOAc and 0.01 g of 18-crown-6 ether in CH_3CN for 30 h. The product was purified by chromatography (EtOAc–hexane 1:4–1:3) to give a mixture of **8a**:**9a** in a ratio of 7:10 in 45% yield (oil). All carbon and hydrogen signals were assigned by COSY and heteroCOSY experiments except for the aromatic carbons for which there is some uncertainty.

2-Phenyl-4-acetoxy-3-hexen-6-olide (8a): ^1H NMR ($CDCl_3$) δ 7.35 (m, 5 H), 5.58 (ddd, J = 6.8, 1.8, 1.2 Hz, H-1), 4.89 (dt, J = 6.8, 2 Hz, H-7), 4.37 (ddd, J = 13, 8.5, 3.2 Hz, H-3), 4.28 (ddd, J = 13, 6.6, 3.6 Hz, H-3), 2.78 (dddd, J = 18.5, 8.5, 3.6, 2 Hz, H-4), 2.52 (ddddd, J = 18.5, 6.6, 3.2, 2, 1.2 Hz, H-4), 2.18 (s, CH_3CO_2); ^{13}C NMR ($CDCl_3$) δ 169.35 (C-7), 169.18 (ester CO,) 149.6 (C-5), 135.6, 129.0, 128.9, 127.7, 113.1 (C-1), 62.2 (C-3), 47.7 (C-7), 32.0 (C-4), 20.8 (CH_3CO); IR (neat) 1731, 1597, 1485, 1217 cm^{-1}; MS CI (isobutane) m/z 247 (MH), 187 (M – HOAc); HRMS calcd for $C_{14}H_{14}O_4$ 246.0891, found 246.0910.

2-Phenyl-4-acetoxy-2-hexen-6-olide (9a): ^1H NMR ($CDCl_3$) δ 7.45 (m, 2 H), 7.35 (m, 3 H), 6.63 (d, J = 5.3 Hz, H-1), 5.63 (ddd, J = 7.6, 6, 5.3 Hz, H-5), 4.42 (m, H-3), 2.75 (m, H-4), 2.15 (m, H-4), 2.09 (s, CH_3CO); ^{13}C NMR ($CDCl_3$) δ 171.8 (C-6), 169.9 (ester (CO), 139.9, 135.0, 133.0 (C-1), 128.6, 127.8, 127.2, 68.9 (C-5), 64.7 (C-3), 32.8 (C-4), 20.8 (CH_3CO).

Reaction of 6 with Sodium Azide. The reaction was carried out in acetone for 10 h using 120 mg (2 equiv) of sodium azide and 0.1 g of $LiClO_4$. A mixture of **19**, **20**, and **21** in a ratio of 1:1:1 was obtained and was separated by chromatography.

2-[1′-(4′-Phenyl-2′-triazolyl)-2′-phenylethyl]-2-azidobutan-4-olide (20). Compound **20** was recrystallized from CH_2Cl_2–petroleum ether to give 50 mg of yellow crystals (25% yield), mp 100 °C: ^1H NMR ($CDCl_3$) δ 7.84 (CH-triazole), 7.74 (m, 2 H), 7.40 (m, 3 H), 7.15 (m, 3 H), 7.01 (m, 2 H), 5.30 (dd, J = 11.6, 2.4 Hz, H-1), 4.38 (td, J = 9, 7 Hz, H-3), 4.30 (td, J = 9, 3 Hz, H-3), 3.64 (dd, J = 13.8, 11.6 Hz, H-7), 3.06 (dd, J = 13.8, 2.4 Hz, H-7), 2.97 (dt, J = 14.5, 9 Hz, H-4), 2.93 (ddd, J = 14.5, 7.2, 2.7 Hz, H-4); ^{13}C NMR ($CDCl_3$) δ 172.3 (C-6), 148.4 (C-tria-

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(17) The numbering of C's and H's in the NMR spectra of **7**, **8**, **9**, **11**, **12**, **16**, **19**, and **20** is based on the numbering of the precursor chloro ketone **6**.

zole), 135.9, 131.6 (CH triazole), 128.8, 128.7, 128.6, 127.1, 126.0, 68.6 (C-1), 67.8 (C-5), 65.9 (C-3), 36.5 (C-7), 30.1 (C-4); MS CI (isobutane) m/z 375 (MH), 347 (M - N_2), 332 (M - HN_3); IR (neat) 2100 1760 cm^{-1}. Anal. Calcd for $C_{20}H_{13}N_6O_2$; C, 64.16; H, 4.85. Found: C, 63.68; H 4.95.

2-Phenacyl-2-buten-4-olide (19). Recrystallization of **19** from CH_2Cl_2 petroleum ether gave 23 mg of white crystals (23% yield): mp 71 °C; ^1H NMR δ 8.01 (m, 2 H), 7.60 (m, H-4 + aromatic H). 4.90 (dd, J = 4, 2 Hz, H-3), 4.02 (dd, J = 4, 2 Hz, H-1); ^{13}C NMR ($CDCl_3$) δ 194.86 (C-7), 173.90 (C-6), 148.48 (C-4), 136.14, 133.67, 128.40, 128.3, 127.15 (C-5), 70.78 (C-3), 34.30 (C-4); IR (neat) 1745, 1682 cm^{-1}. MS CI (isobutane) m/z 203 (MH), 175 (M - CO). Anal. Calcd for $C_{12}H_{10}O_{13}$: C, 70.99; H, 4.99. Found: C, 70.99; H, 5.01.

Reaction of 6 with Sodium Hydroxide. Reflux was carried out in CH_3CN-H_2O (9:1) for 7 h with 50 mg (1.5 equiv) of NaOH to give a mixture of **12a:12b** in a ratio of 2:1. The two isomers were separated by chromatography (EtOAc–hexane (1:3–2:1)).

8α-Phenyl-2,7-dioxabicyclo[3.3.0]octan-6-one (12a) was obtained as a colorless oil in 25% yield (46 mg): ^1H NMR ($CDCl_3$) δ 7.38 (m, 5 H) 5.59 (d, J = 4 Hz, H-7), 4.73 (dd, J = 5.5, 4 Hz, H-1), 3.81 (dd, J = 8, 5.5 Hz, H-3), 3.45 (ddd, J = 9, 5.5, 2 Hz, H-5), 2.47 (dtd, J = 12.5, 5.5, 2 Hz, H-4), 2.29 (dq, J = 12.5, 8.5 Hz, H-4); ^{13}C NMR ($CDCl_3$) δ 178.1 (C-6), 134.1, 128.4, 128.3, 126.1, 83.4, 81.0 (C-1, C-7), 68.4 (C-3), 46.5 (C-5), 29.7 (C-4); MS CI (isobutane) m/z 205 (MH), 187 (M - CO).

8β-Phenyl-2,7-dioxabicyclo[3.3.0]octan-6-one (12b). The β isomer was obtained as a solid in 40% yield and recrystallized from petroleum ether–CH_2Cl_2. It gave 75 mg of white crystals, mp 54 °C: ^1H NMR ($CDCl_3$) δ 7.36 (m, 5 H), 5.55 (s, H-7), 4.54 (d, J = 6 Hz, H-1), 3.96 (td, J = 9, 4.5 Hz, H-3), 3.93 (dt, J = 9, 6 Hz, H-3), 3.36 (ddd, J = 9, 6, 2.5 Hz, H-5), 2.40 (dddd, J = 12.5, 6, 4.5, 2.5 Hz, H-4), 2.26 (dq, J = 12.5, 9 Hz, H-4); ^{13}C NMR ($CDCl_3$) δ 178.2 (C-6), 137.6, 129.0, 128.5, 124.9, 85.9, 85.6 (C-7, C-1), 69.1 (C-3), 44.1 (C-5), 30.1 (C-4); IR (neat) 1766, 1492, 1442, 1146 cm^{-1}; MS CI m/z 205 (MH), 185 (M - CO). Anal. Calcd for $C_{12}H_{12}O_3$: C, 70.56; H, 5.92. Found: C, 5.92; H, 6.57.

Reaction of 6 with Sodium Methoxide. The solution of sodium methoxide was prepared by addition of 22 mg (1:1 equiv) of Na to 10 mL of dry MeOH under Ar. Forty min after addition of **6** at 25 °C reaction was completed. The solvent was evaporated in vacuum, the residue was dissolved in CH_2Cl_2, washed with saturated NaCl, dried over $MgSO_4$, and the solvent was evaporated to yield 170 mg of **11b** (89%).

2-Phenyl-4-methoxy-4-(2-hydroxyethyl)-2-cyclobuten-1-one (11b): ^1H NMR ($CDCl_3$) δ 8.60 (s, H-1), 7.75 (m, 2 H), 7.42 (m, 3 H), 3.86 (ddd, J = 6.5, 5, 3 Hz, H-3), 3.35 (s, OMe), 2.13 (dt, J = 6, 5 Hz, H-4); ^{13}C NMR ($CDCl_3$) δ 194.9 (C-6), 161.2 (C-1), 153.1 (C-7), 130.4, 129.3, 128.4, 127.5, 98.5 (C-5), 58.67 (C-3), 52.8 (OMe), 36.9 (C-4); IR (neat) 3480, 2840, 1750 cm^{-1}; MS CI (isobutane) m/z 219 (MH).

2-Phenyl-4-methoxy-3-hexen-6-olide (8b). A solution of **11b** in dry benzene was refluxed for 7 h, the solvent evaporated in vacuum, and the residue purified by chromatography (petroleum ether–CH_2Cl_2 (1:1)) to yield 100 mg (60%) of **8b**, mp 145 °C: ^1H NMR ($CDCl_3$) δ 7.32 (m, 5 H), 4.84 (dt, J = 6.5, 1.5, H-1), 4.73 (d, J = 6.5 Hz, H-7), 4.27 (ddd, J = 6, 4.5, 2 Hz, H-3), 3.60 (s, OMe), 2.65 (ddd, J = 18.5, 6, 1.5 Hz, H-4), 2.52 (ddddd, J = 18.5, 5.5, 4.5, 1.5, 1 Hz, H-4); ^{13}C NMR ($CDCl_3$) δ 172.5 (C-6), 157.1 (C-5), 138.7, 128.8, 127.2, 127.5, 92.3 (C-1), 62.9 (C-3), 54.7 (C-7), 47.0 (OMe), 32.8 (C-4); IR 1730, 1650 cm^{-1}; MS CI m/z (isobutane) 219 (MH), 257 (M + C_3H_7); HRMS calcd for $C_{13}H_{14}O_3$ 218.09418, found 218.0943.

Reaction of 6 with Potassium Thiophenoxide (KSPh). To a stirred solution of 1.1 equiv of KSPh (110 μL of PhSH) in dry THF under Ar was added a solution of 0.2 g of **6**. The mixture was stirred for 1.5 h, and 2 mL of 5% HCl was added. The solvent was evaporated and the residue dissolved in CH_2Cl_2 and washed twice with saturated NaCl. The solvent was evaporated and the product purified by chromatography (CH_2Cl_2–petroleum ether (1:1)) to give 150 mg (55%) of **15** in (oil).

7-Phenyl-7-(phenylthio)-2-oxabicyclo[3.2.0]heptan-6-one (15): ^1H NMR ($CDCl_3$) δ 7.25 (m, 10 H), 4.91 (d, J = 6 Hz, H-1), 4.19 (ddd, J = 9, 5, 1.5 Hz, H-3), 3.91 (ddd, J = 9, 8, 1.5 Hz, H-3), 3.29 (ddd, J = 13, 9, 6 Hz, H-1), 2.19 (ddt, J = 13, 5, 1 Hz, H-4), 1.94 (dddd, J = 13, 12, 9, 8 Hz, H-4); ^{13}C NMR ($CDCl_3$) δ 204.8 (C-6), 136.4, 134.1, 129.3, 128.6, 128.1, 128.0, 127.6, 79.4 (C-1), 73.6 (C-7), 68.9 (C-3), 62.0 (C-5), 28.9 (C-4); IR (neat) 3048, 1766, 1590, 1471 cm^{-1}; MS CI (isobutane) m/z 297 (MH), 339 (M + C_3H_7), 189 (M - PhSH); HRMS calcd for $C_{18}H_{16}O_2S$ 296.0869, found 296.0886.

3-(Phenylthio)-12,13-dihydronaphthofuran (16). A mixture of 0.1 g (0.34 mmol) of **15** and a catalytic amount of *p*-TsOH in $CDCl_3$ was refluxed overnight. The mixture was washed with 5% $NaHCO_3$ and saturated NaCl solution and dried. The residue was chromatographed (EtOAc–hexane (1:5)) to give 55 mg of white crystals (60%), mp 112 °C: ^1H NMR ($CDCl_3$) δ 8.3 (broad d, J = 8 Hz, 1 H), 7.55 (d, J = 8 Hz, 1 H), 7.44 (s, 1 H), 7.35 (m, 1 H), 7.10 (m, Ph), 4.72 (t, J = 8 Hz, H-3), 3.45 (td, J = 8, 1.5 Hz, H-4); ^{13}C NMR ($CDCl_3$) δ 129.3, 129.2, 128.7, 128.0, 127.0, 126.3, 126.0, 124.90, 124.7, 123.8, 71.7 (C-3), 29.9 (C-4); MS CI (isobutane) m/z 270 (MH) 245.

Reaction of 6 with Diethylpotassium Malonate. To a dry flask under Ar were added 110 mg (1 mmol) of potassium *tert*-butoxide and 150 mg of diethyl malonate (1 mmol) in 10 mL of dry THF. The solution was stirred for 15 min at 25 °C, 0.2 g (0.9 mmol) of **6** in 3 mL of THF was added, and stirring was continued for 3 h. After 3 mL of 5% HCl was added, the layers were separated and the organic layer was washed successively with 5% $NaHCO_3$ and saturated NaCl and dried over $MgSO_4$. The solvent was evaporated to give a mixture of **18a–c** which was purified by chromatography (EtOAc–hexane (1:5–1:3)).

5-[Bis(ethoxycarbonyl)methyl]-7-phenyl-7-chloro-2-oxabicyclo[3.2.0]heptan-6-one (18c). The product (85 mg, 25%) was obtained as an oil: ^1H NMR ($CDCl_3$) δ 7.55 (m, 2 H), 7.38 (m, 3 H), 5.20 (s, H-1), 4.28 (q, J = 7 Hz, CH_2CH_3), 4.19 (s, malonate CH), 3.92 (ddd, J = 9, 8.5, 3.5 Hz, H-3), 3.28 (td, J = 9, 7 Hz, H-3), 2.38 (ddd, J = 14.7, 3 Hz, H-4), 2.28 (ddd, J = 14, 9.5, 8 Hz, H-4), 1.34 (t, J = 7 Hz, CH_3), 1.31 (t, J = 7 Hz, CH_3); ^{13}C NMR ($CDCl_3$) δ 201.9 (C-6), 166.4, (CO_2Et), 133.2, 130.0, 128.7, 128.3, 86.1 (C-1), 72.3 (C-7), 69.6 (C-3), 62.2, 62.0 (OCH_2CH_3), 54.2 (CH malonate), 32.36 (C-4), 14.01, 13.97 (CH_3); IR (neat) 1790, 1645, 1435 cm^{-1}; MS CI (isobutane) m/z 381 (M + 1), 419 (M + C_3H_7), 345 (M - Cl), 335 (M - EtOH). Anal. Calcd for $C_{19}H_{21}O_6Cl$: C, 59.99; H, 5.56, found: C, 60.33; H, 5.53.

5-[Bis(ethoxycarbonyl)methyl]-7-phenyl-2-oxabicyclo[3.2.0]heptan-6-one (18a) and (18b). The oily product (50 mg, 30%) was obtained as a mixture of trans–cis **18a:18b** (designated by t and c subscripts) isomers in a ratio of 10:7: ^1H NMR ($CDCl_3$) δ 7.30 (m, aromatic H), 5.37 (d, J = 7.5 H-1$_t$), 5.22 (d, J = 5 Hz, H-1$_c$), 5.07 (d, J = 7.5, H-7$_t$), 4.44 (d, J = 5 Hz, H-7$_c$), 4.22 (m, H-3$_c$), 4.18 (dq, J = 7, 2 Hz, OCH_2CH_{3t}), 4.05 (dq, J = 7, 2 Hz, OCH_2CH_{3c}), 3.94 (s, CH malonate$_t$), 3.87 (s, CH malonate$_c$), 3.86 (td, J = 9, 1.5, H-3$_t$), 3.33 (ddd, J = 11, 9, 5.5, H-4$_t$), 2.42 (ddd, J = 14.7, 4 Hz, H-4$_c$), 2.24 (m, H-4$_c$), 2.20 (m, H-4$_t$), 1.98 (ddd, J = 13, 11, 8 Hz, H-4$_t$), 1.30, 1.29 (t, J = 7 Hz, OCH_2CH_{3t}), 1.23, 1.15 (t, J = 7 Hz, OCH_2CH_{3c}); ^{13}C NMR ($CDCl_3$) δ 209.8 (C-6$_t$), 205.3 (C-6$_c$), 167.3, 167.0, 166.9, 166.7 (ester CO), 134.4, 132.5, 128.6, 128.4, 127.2, 127.0, 126.8, 80.2 (C-1$_t$), 77.3 (C-1$_c$), 72.2 (C-5$_c$), 70.1 (C-1$_t$), 67.9 (C-3$_c$), 67.3 (C-3$_t$), 65.8, 64.6, 62.1, 62.0 ($CO_2CH_2CH_3$), 54.3 (C-7$_c$), 54.1 (C-6$_t$), 34.1 (C-4$_t$), 32.3 (C-4$_c$), 14.0, 14.0, 13.5 (CH_3); IR (neat) 3422, 1780, 1724 cm^{-1}; MS CI (isobutane) m/z 347 (MH), 329 (M - H_2O).

Acknowledgment. We thank Dr. H. E. Gottlieb for assistance with NMR spectral analyses. We are grateful to the E. Alec Colman Scholarship Fund for a fellowship to S.N.-M.

Supplementary Material Available: ^{13}C NMR spectra of **8a, 9, 8b, 12a, 15, 16,** and **18a,b** (6 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.