Intermolecular and Intramolecular Azomethine Ylide [3 + 2] Dipolar Cycloadditions for the Synthesis of Highly Functionalized Pyrroles and Pyrrolidines

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Received August 13, 1984

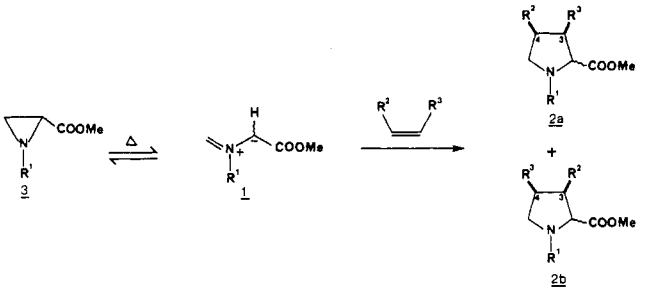
N-Alkyl- and *N*-arylaziridines carrying a single carboxy ester function undergo thermally induced electrocyclic ring opening to produce azomethine ylides which subsequently react with acetylenes or olefins to yield substituted pyrroles or pyrrolidines, respectively. The [3 + 2] dipolar cycloaddition reaction can be performed in either an intermolecular or intramolecular mode and displays high regioselectivity and stereoselectivity with a variety of dipolarophiles. The yield of cycloadducts depends upon the electronic characteristics and the substitution pattern of the dipolarophile and upon the mode of cycloaddition employed. In the intermolecular reaction, the yield of adducts is poor unless the dipolarophile is activated. Intramolecular cycloadditions with monosubstituted olefins or acetylenes give adducts in yields of 45–70%. Although the yields of adducts in these instances are moderate, the starting materials are readily prepared and the method is an effective means for the assembly of a structurally complex heterocyclic system with high regiochemical and stereochemical control of peripheral substituents. In those instances in which the dipolarophilic component is disubstituted, the cycloaddition gives synthetically useful yields when the dipolarophile carries an electron-withdrawing functionality.

The dipolar cycloaddition of an azomethine ylide **1** with an olefin is a very useful reaction because it creates two carbon–carbon bonds in a single operation and results in the formation of a pyrrolidine **2** in which high regio- and stereochemical control of the peripheral substituents can be achieved. From the pioneering studies of Huisgen,[1] and later studies by Grigg,[2] Joucla,[3] Carrie,[4] and others,[5] several generalities have emerged concerning azomethine ylide cycloadditions. The regiochemistry observed in the cycloaddition (**2a** vs. **2b**) depends upon the electronic characteristics of the substituents carried by the dipolarophile. That is, electron-withdrawing groups orient the dipolarophile such that the pyrrolidine carries this group at C-4.

Secondly, the relative stereochemistry at C-3/C-4 in the cycloadduct is dictated by the geometry of the dipolarophile. Thus, *Z* olefins lead to the syn relationship between the substituents in adduct **2**, while the anti stereochemistry results from E olefins. Since olefin geometry is readily controlled by modern methodology, the task of establishing stereochemical relationships between substituents at C-3 and C-4 is facilitated in the azomethine ylide approach (see Scheme I).

The full potential of the azomethine ylide cycloaddition as a means of synthesizing pyrrolidine-containing natural products has not been exploited due to the problems involved with the generation of the ylide and the limited reactivity of olefins lacking electron-withdrawing groups in the cycloaddition reaction. Recently, the groups of Vedejs,[6] Livinghouse,[7] Padwa,[8] Confalone,[9] and Kraus[10] have reported new methods for the generation of azomethine ylides **1** from imines or iminium salts.

Scheme I



Huisgen[1] and others[3-5] have demonstrated that aziridine rings which have *two* stabilizing functionalities such as carboxy ester groups or phenyl rings undergo thermal ring opening and subsequent cycloaddition with *reactive* dipolarophiles (i.e., maleic anhydride, *N*-phenylmaleimide, etc.) to produce pyrrolidines in excellent yields. However, it has never been demonstrated that the aziridine approach to azomethine ylides can be generated from aziridines such as **3** which carry a single ylide stabilizing substituent. Neither is it known whether these ylides will react with dipolarophiles which lack multiple electron-withdrawing substituents. Therefore, we embarked upon an investigation of the azomethine ylide reaction with two goals: (a) to determine whether aziridine **3** could function as a precursor of azomethine ylides and (b) to ascertain whether acrylate and propiolate esters or vinyl ethers could participate in the cycloaddition. We believe that the cycloadducts obtained from these reactions can serve as valuable intermediates in the synthesis of alkaloidal natural produces which contain highly substituted pyrrolidine systems.

Results and Discussion

Our results, summarized in Table I, indicate that aziridines **4** and **9** can function as a source of azomethine ylides

(1) Huisgen, R. *Angew. Chem., Int. Ed. Engl.* **1963**, *2*, 565, 633, and references cited therein. Huisgen, R.; Scheer, W.; Huber, H. *J. Am. Chem. Soc.* **1967**, *89*, 1753. Huisgen, R.; Scheer, W.; Mader, H. *Angew. Chem., Int. Ed. Engl.* **1969**, *8*, 602. Hall, J. H.; Huisgen, R. *J. Chem. Soc., Chem. Commun.* **1971**, 1187. Hall, J. H.; Huisgen, R.; Ross, C. H.; Scheer, W. *Ibid.*, 1188.

(2) Grigg, R.; Kemp, J.; Sheldrick, G.; Trotter, J. *J. Chem. Soc., Chem. Commun.* **1978**, 109 and references cited therein. Grigg, R.; Kemp, J. *Tetrahedron Lett.* **1978**, 2823.

(3) Joucla, M.; Hamelin, J. *Tetrahedron Lett.* **1978**, 2885.

(4) Benhaoua, H.; Texier, F.; Guenot, P.; Martelli, J.; Carrie, R. *Tetrahedron* **1978**, *34*, 1153.

(5) Gelas-Mialhe, Y.; Hierle, R.; Vessiere, R. *Bull. Soc. Chim. Fr.* **1974**, 709. Attia, M.; Gelas-Mialhe, Y.; Vessiere, R. *Chem. Lett.* **1979**, 1095. Imai, N.; Terao, Y.; Achiwa, K.; Sekiya, M. *Tetrahedron Lett.* **1984**, *25*, 1579. Rentrakul, V.; Prapansiri, V.; Panyachotipun, C. *Ibid.* **1984**, *25*, 1949. Grigg, R.; Aly, M. F.; Sridharan, V.; Thianpatanagul, S. *Ibid.*, 182.

(6) Vedejs, E.; Martinez, G. R. *J. Am. Chem. Soc.* **1980**, *102*, 7993.

(7) Smith, R.; Livinghouse, T. *J. Org. Chem.* **1983**, *48*, 1554.

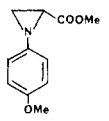
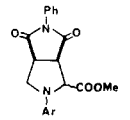
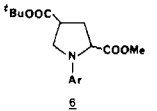
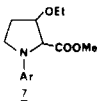
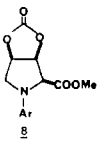
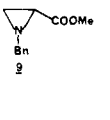
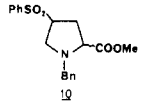
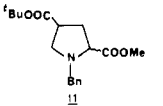
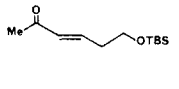
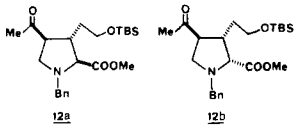
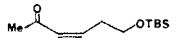
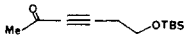
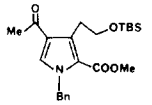
(8) Padwa, A.; Haffmanns, G.; Tomas, M. *Tetrahedron Lett.* **1983**, *24*, 4303.

(9) Confalone, P. N.; Huie, E. M. *J. Org. Chem.* **1983**, *48*, 2994.

(10) Kraus, G.; Nagy, J. O. *Tetrahedron Lett.* **1983**, *24*, 3427.

0022-3263/85/1950-2309$01.50/0

Table I. Intermolecular Azomethine Ylide Cycloadditions of Aziridines 4 and 9

aziridine	dipolarophile	cycloadduct	yield, %[a]
 4		 5	48[b]
"		 6	15[b]
"		 7	42[c]
"		 8	60
 9		 10	17[d]
"		 11	30[e]
"		 12a 12b	66[f]
"		—	0
"		 13	22

TBS = t-butyldimethylsilyl

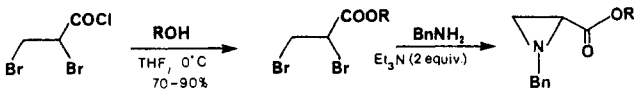
[a] Based upon consumed aziridine. Recovered aziridine comprised ≤20% of the reaction mixture. [b] Mixture of two diastereomers. [c] Single diastereomer; relative stereochemistry not determined. [d] Two diastereomers in a ratio of 4.1:1. [e] Diastereomer ratio undetermined. [f] Two diastereomers, **12a**:**12b**, in a ratio of 1:11.

1 under thermal conditions, and that dipolarophiles such as *N*-phenylmaleimide and vinylene carbonate gave pyrrolidines in good yield. Less reactive dipolarophiles, for instance *tert*-butyl acrylate and phenyl vinyl sulfone gave low yields of the cycloadducts. It should be noted, however, that the cycloaddition displayed complete regioselectivity, producing only the 2,4-substititon pattern, as expected.

We observed the opposite regiochemistry (2,3 instead of 2,4) in the cycloaddition of ethyl vinyl ether with aziridine 4. This reversal of the regiochemistry was expected based upon the MO calculations of Houk[11] who had predicted that electron-rich olefins such as vinyl ethers would react with 1,3-dipoles to give adducts with the reversed stereochemistry. *This is the first example of an azomethine ylide cycloaddition in which an electron-rich olefin serves as the dipolarophile.*[12]

(11) Houk, K. N.; Sims, J.; Watts, C. R.; Luskus, L. J. *J. Am. Chem. Soc.* **1973**, *95*, 7301 and references cited therein.

Scheme II



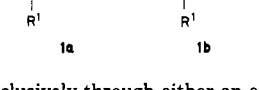
Aziridine 4 also reacts with vinylene carbonate to produce pyrrolidine 8 in 60% yield. A single stereoisomer of the cycloadduct was obtained and was assigned the syn,syn stereochemistry based upon the observed C-2/C-3 coupling constant of 7 Hz. The alternative stereochemistry at C-2/C-3 would force the two protons to adopt a dihedral angle of approximately 90° and would result in a small coupling constant (J = 1–2 Hz).[13,14]

Unactivated olefins such as O-protected allylic alcohols, cyclohexene, and styrene failed to yield cycloadducts under the intermolecular conditions. These results are not surprising since molecular orbital calculations[11] predict the olefins lacking either electron-withdrawing or electron-donating substituents should be the least reactive dipolarophiles in the reaction.

The intramolecular variant of the [3 + 2] dipolar cycloaddition was also investigated. The requisite aziridines are readily assembled by the sequence of reactions shown in Scheme II.[15] Cycloadditions of the aziridines were performed at temperatures between 300–400 °C by using the flash vacuum pyrolysis (FVP) system described by Fowler[16] and the results of the intramolecular reactions are summarized in Table II. It is critical to the success of the intramolecular reaction that FVP conditions be employed since attempts to perform the intramolecular cycloaddition in a sealed tube in solution resulted in extensive decomposition of the starting aziridines without producing cycloadducts. In marked contrast to the intermolecular cycloaddition, the intramolecular version of the reaction leads to the formation of pyrrolidines *even with olefins lacking electron-donating or withdrawing substituents.*

Aziridines **14** and **16**, in which the olefinic portion of the molecule is activated toward [3 + 2] dipolar cycloaddition by the attachment of an electron-withdrawing substituent,

(12) It is noteworthy that the cycloaddition produced a single stereoisomer of **7** (of unknown relative stereochemistry at present). This result suggests that the ylide which was generated in the reaction adopts only one of the two possible ylide conformations, **1a** or **1b**, and that the dipolarophile reacts exclusively through either an endo or exo transition state. However, from this single result it is not possible to unambiguously define either the geometry of the ylide or the nature of the transition state.



1a **1b**

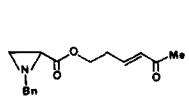
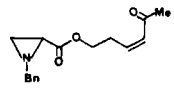
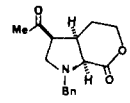
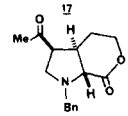
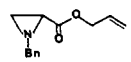
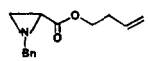
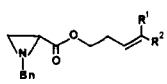
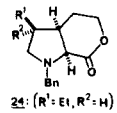
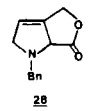
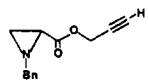
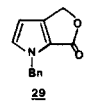
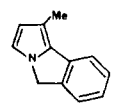
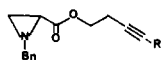
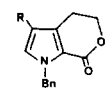
(13) Jackman, L.; Sternhell, S. "Applications of Nuclear Magnetic Resonace in Organic Chemistry"; 2nd ed.; Oxford: Pergamon Press, 1969; pp 281–304.

(14) The high stereoselectivity observed in the cycloaddition of aziridine **4** with ethyl vinyl ether and vinylene carbonate appears to be a general phenomenon and indicates that a unique ylide geometry and transition-state orientation are involved in the cycloadditions, but at this point it is not possible to define the stereochemical requirements of the reaction. We are presently engaged in additional studies designed to elucidate the factors which control the stereochemistry of the cycloaddition.

(15) Stolberg, M.; O'Neill, J.; Wagner-Jauregg, T. *J. Am. Chem. Soc.* **1953**, *75*, 5045.

(16) Beeken, P.; Bonfiglio, J. N.; Hasan, I.; Piwinski, J. J.; Weinstein, B.; Zollo, K. A.; Fowler, F. W. *J. Am. Chem. Soc.* **1979**, *101*, 6677.

Table II. Intramolecular Azomethine Ylide Cycloadditions

aziridine	cycloadduct	yield, %
 14	 15	80
 16	 17  18	52[a]
 19	 20	67
 21	 22	69
 23: (R¹=Et, R²=H) 25: (R¹=H, R²=Et)	 24: (R¹=Et, R²=H) 26: (R¹=H, R²=Et)	16 26
	 28	35
 27	 29	8
	 30	3 (40[b])
 31: (R=H) 33: (R=Et)	 32: (R=H) 34: (R=Et)	63 34

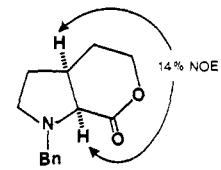
[a] Two diastereomers, 17 and 18 in a 1.1:1 ratio. [b] FVP of aziridine 27 followed by treatment of the reaction with NiO_2 gave pyrrole 30 in 40% yield.

gave improved yields of adducts in the intramolecular version of the reaction. Flash vacuum pyrolysis of (*E*)-enone 14 gave a single cycloadduct 15 in a yield of 80%. The cis ring fusion of 15 was indicated by the magnitude of the coupling constant ($J_{2,3}$ = 10 Hz) observed in the adduct.[13]

Aziridine 16 in which the olefin geometry is cis rather than trans also undergoes FVP-induced cycloaddition to produce two pyrrolidines, 17 and 18, as a 1:1 mixture in a combined yield of 52%. Pyrrolidine lactone 17 has the cis ring fusion, while the other isomer, 18, possesses the trans fusion. The stereochemical assignments for 17 and 18 are based upon two pieces of spectroscopic evidence. First, the magnitudes of the C-2/C-3 coupling constants in 17 and 18 are 9 and 12 Hz, respectively. The smaller of these coupling constants is identical with that observed in other adducts in which the cis ring fusion was indicated (vide infra). The larger coupling constant (12 Hz) indicates that the two protons at the ring junction have an antiperiplanar (180°) relationship[13] and thus must be trans. The infrared spectra of the isomers further corroborates this stereochemical assignment. Lactone 17 displays carbonyl stretching bands at 1755 and 1720 cm^{-1}, while 18 shows stretching bands at 1775 and 1720 cm^{-1}. The higher stretching frequency indicates that the lactone ring in isomer 18 is more strained.

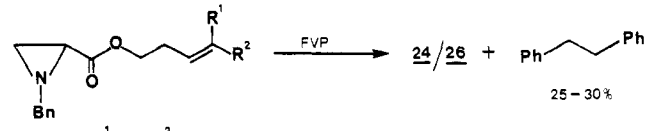
The success of the intramolecular cycloaddition with the *Z* olefin (16) contrasts sharply with the results obtained in the intermolecular cycloaddition of aziridine 9 and *Z* enone which failed to give a cycloadduct (vide supra). Also, under the flash vacuum conditions the *Z* enone did not undergo olefin isomerization.

Unactivated dipolarophiles such as allylic alcohols function satisfactorily as dipolarophiles in the intramolecular version of the azomethine ylide cycloaddition as evidenced by the results obtained with aziridines 19 and 21. In both instances, a single stereoisomer of adducts 20 and 22, respectively, was produced in good yield. The cis ring fusion in the products was confirmed by nuclear Overhauser effect difference spectroscopy (NOEDS).[17] For instance, in 22, a 14% enhancement in the C-2 signal was observed upon irradiation of the proton at C-3. The magnitude of the NOE is a clear indication that the protons are syn.



22

Attachment of an alkyl substituent onto the dipolarophilic portion of the molecule resulted in a dramatic decrease in the yield of pyrrolidine produced in the cycloaddition reaction. For instance, pyrolysis of aziridines 23 or 25 resulted in the formation of pyrrolidines 24 and 26 in yields of only 16 and 26%, respectively. A major byproduct of the reaction of aziridines 23 and 25 was 1,2-diphenylethane, which presumably arose from the coupling of two benzyl radicals. This byproduct generally constituted 25–30% of the reaction product and suggests that the starting materials undergo extensive radical degradation which were decreasing the yields of the pyrrolidines. However, attempts to isolate debenzylated pyrrolidines from the reaction mixtures were unsuccessful.



23: R^1=Et, R^2=H
25: R^1=H, R^2=Et

Dipolar cycloaddition of azomethine ylides with acetylenes is expected to produce 2,5-dihydropyrroles as the primary cycloadducts, and aziridine 27 gave the expected

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produce, dihydropyrrole **28**. However, depending upon the reaction conditions employed, varying amounts of pyrrole **29**, arising from aromatization of **28**, were also produced. Traces of tricyclic pyrrole **30**, formed by oxidation of either **28** or **29**, were also obtained. Aromatization of **28** to **29** could be achieved by exposing the crude cycloaddition reaction mixture to oxygen for 24 h.

Attempted aromatization of dihydropyrrole **28** with NiO_2[18] resulted in the formation of tricyclic pyrrole **30** in excellent yield. Subsequently, it was shown that treatment of *N*-benzylpyrrole **29** with NiO_2 also gave tricyclic pyrrole **30**.

Intramolecular cycloaddition of aziridines **31** and **33** resulted directly in formation of pyrroles **32** and **34**, respectively. Unlike the results obtained from aziridine **27**, the primary cycloadduct, the dihydropyrrole was not detected in either reaction mixture. Presumably, in the less strained 5,6-ring system aromatization of the dihydropyrroles occurred under the reaction conditions.

Conclusions

N-Alkyl- and *N*-arylaziridines carrying a single carboxy ester function undergo thermally induced electrocyclic ring opening to produce azomethine ylides which subsequently react with acetylenes or olefins to yield substituted pyrroles or pyrrolidines, respectively. The [3 + 2] dipolar cycloaddition reaction can be performed in either an intermolecular or intramolecular mode and displays high regioselectivity and stereoselectivity with a variety of dipolarophiles. The yield of cycloadducts depends upon the electronic characteristics, the substitution pattern of the dipolarophile, and the mode of cycloaddition employed. In the intermolecular reaction, the yield of adducts is poor unless the dipolarophile is activated. Intramolecular cycloadditions with monosubstituted olefins or acetylenes give adducts in yields of 45–70%. Although the yields of adducts in these instances are moderate, the starting materials are readily prepared and the method is an effective means for the assembly of a structurally complex heterocyclic system with high regiochemical and stereochemical control of peripheral substituents. In those instances in which the dipolarophilic component is disubstituted, the cycloaddition gives synthetically useful yields when the dipolarophile carries an electron-withdrawing functionality.

Experimental Section

Aziridine 4. Methyl acrylate (9.56 g, 111 mmol) was added to *p*-methoxyphenyl azide[20] (15.3 g, 102 mmol) and the solution was stirred in the dark until the azide (IR 2100 cm^{-1}) was consumed (14d). Evaporation of the excess acrylate (15 mm) provided a brown oil that was heated to 33 °C (18 h, 15 mm) until the evolution of gas ceased. The oil was then warmed to 50 °C (0.05 mm) and the aziridine sublimed onto a cold finger (light yellow crystals, 10.6 g, 50%). A second sublimation gave aziridine **4** as white needles: mp 46–48 °C; IR (CCl_4) 1750 (s), 1730 (s), 1500 (s), 1240 (s), 1195 (s), 1175 (s); ^1H NMR ($CDCl_3$) 6.80 (m, 4), 3.75 (s, 3), 3.70 (s, 3), 2.65 (m, 2), 2.25 (dd, 1, J = 2,6); mass spectrum, m/z (relative intensity) 207 (M^+, 57), 192 (29), 148 (47), 132 (100).

Aziridine 9. A modification of the procedure described by Stolberg[15] gave aziridine **9**: 98%, colorless oil; bp 105–112 °C (0.02 mm) [lit.[15] bp 96–98 °C (0.2 mm)]; IR (film) 1750 (vs), 1435 (s), 1190 (s), 1170 (s), 1070 (m); ^1H NMR ($CDCl_3$) 7.32 (m, 5), 3.72 (s, 3), 3.55 (s, 2), 2.24 (m, 2), 1.77 (dd, 1, J = 1.2, 6.4); mass spectrum, m/z (relative intensity) 191 (M^+, 7), 176 (9), 132 (26), 104 (26), 100 (12), 91 (100).

General Procedure for Sealed Tube Cycloadditions. A solution of aziridine, dipolarophile, and solvent in a dry thick-walled carius tube was degassed three times and sealed under argon. The solution is heated until complete loss of aziridine, monitored by TLC. The solvent was removed in vacuo and excess dipolarophile vacuum distilled, if possible. Products were isolated by chromatography of the residue.

Pyrrolidine 5. Aziridine **4** (54 mg, 0.26 mmol), *N*-phenylmaleimide (150 mg, 0.87 mmol), and toluene were heated at 145 °C for 16.5 h. PLC (20 × 20 cm, 0.5 mm silica gel, 4:1 CH_2Cl_2–EtOAc) gave **5** as a mixture of diastereomers: 40 mg (48%). Repeated PLC gave pure samples for spectral analysis. 2,3-*anti*-3,4-*syn*-Pyrrolidine **5**: IR (CCl_4) 1755 (w), 1735 (m), 1715 (vs), 1235 (s), 1165 (m); ^1H NMR ($CDCl_3$) 7.38 (m, 5), 6.78 (ABq, 4, J = 13), 4.96 (s, 1), 4.00 (dd, 1, J = 1, 10), 3.76 (s, 3), 3.70 (s, 3), 3.69 (m, 2); mass spectrum, m/z (relative intensity) 380 (M^+, 20), 321 (100), 174 (78), 159 (10), 134 (8). 2,3-*syn*-3,4-*syn*-Pyrrolidine **5**: IR (CCl_4) 1755 (w), 1730 (m), 1715 (s), 1240 (vs), 1165 (m); ^1H NMR ($CDCl_3$) 7.39 (m, 5), 6.78 (ABq, 4, J = 9), 4.62 (d, 1, J = 9), 4.10 (dd, 1, J = 3, 9), 3.96 (t, 1, J = 9), 3.76 (s, 3), 3.71 (dd, 1, J = 3, 9), 3.68 (d, 1, J = 9), 3.68 (s, 3); mass spectrum, m/z (relative intensity) 380 (M^+, 14), 321 (100), 174 (78), 159 (10), 134 (8).

Pyrrolidine 6. Aziridine **4** (15 mg, 0.052 mmol) and *tert*-butyl acrylate (890 mg, 6.9 mmol) were heated at 125 °C for 41 h. PLC (20 × 20 cm, 0.5 mm silica gel, CH_2Cl_2, 6 elutions) provided **6**: 3 mg (15%); IR (CCl_4) 3040 (w), 2975 (s), 1725 (vs), 1365 (s), 1150 (vs); ^1H NMR ($CDCl_3$) 6.74 (ABq, 4, J = 9), 4.60 (m, 1), 3.74 (s, 3), 3.73 (m, 2), 3.65 (s, 3), 3.17 (m, 1), 2.89 (m, 1), 2.80 (m, 1), 1.45 (s, 9); mass spectrum, m/z (relative intensity) 335 (M^+, 17), 278 (100), 234 (5), 219 (8), 174 (18), 77 (10), 56 (41).

Pyrrolidine 7. Aziridine **4** (140 mg, 0.48 mmol) and ethyl vinyl ether (9.05 g, 125 mmol) were heated at 125 °C for 13 days. Column chromatography (10 g silica gel, 7:3 hexane–EtOAc) gave **7**: 73 mg (42%); IR (CCl_4) 1770 (s), 1730 (vs), 1295 (s), 1240 (vs), 1185 (s), 1045 (s); ^1H NMR ($CDCl_3$) 6.75 (ABq, 4, J = 9), 4.62 (m, 1), 4.53 (m, 1), 4.14 (q, 2, J = 7), 3.74 (s, 3), 3.65 (s, 3), 3.60 (m, 1, 3.50 (m, 1), 2.35 (m, 1), 2.15 (m, 1), 1.16 (t, 3, J = 7); mass spectrum, m/z (relative intensity) 279 (M^+, 15), 234 (100), 134 (22), 107 (5), 92 (4), 77 (8).

Pyrrolidine 8. Aziridine **4** (200 mg, 0.97 mmol), vinylene carbonate (219 mg, 2.50 mmol), and benzene were heated at 160 °C for 3 days. Recrystallization from ether gave **8**: 170 mg (60%); white powder; mp 140–141 °C; IR (KBr) 1815 (s), 1800 (s), 1730 (s), 1515 (s), 1145 (s), 1065 (s); ^1H NMR (acetone-d_6) 6.77 (m, 4), 5.68 (t, 1, J = 7.0), 5.50 (ddd, 1, J = 1.0, 5.0, 7.0), 4.45 (d, 1, J = 7.0), 4.00 (dd, 1, J = 1.0, 11.5), 3.71 (s, 6), 3.50 (dd, 1, J = 5.0, 11.5); mass spectrum, m/z (relative intensity) 293.0898 (M^+, 22), 234.0766 (100). Anal. Calcd for $C_{14}H_{15}NO_6$: C, 57.34; H, 5.16; N, 4.78. Found: C, 57.42; H, 5.21; N, 4.75.

Pyrrolidine 10. Aziridine **9** (92 mg, 0.48 mmol), phenyl vinyl sulfone (565 mg, 3.4 mmol), and xylene were heated at 150 °C for 2 days. Excess phenyl vinyl sulfone crystallized from Et_2O–hexane. Flash chromatography (1:1 Et_2O–hexane) of the mother liquor gave **10** (4.1:1 mixture of isomers): 30 mg (17%); yellow oil; IR ($CHCl_3$) 1735 (m), 1320 (s), 1300 (s), 1135 (vs), 1065 (s); ^1H NMR ($CDCl_3$) 7.63 (m, 10), 4.77 (d, 1, J = 8.3), 3.98 (d, 1, J = 9.5), 3.95 (m, 1), 3.83 and 3.77 (2 s, 3), 3.68 (m, 1), 3.32 (m, 1), 2.90 (dd, 1, J = 8.5, 13.6), 2.62 (m, 1), 2.56 (dd, 1, J = 9.5, 13.6); mass spectrum CI, CH_4), m/z (relative intensity) 360 (M + 1^+, 100), 300 (13).

Pyrrolidine 11. Aziridine **9** (103 mg, 0.37 mmol) and *tert*-butyl acrylate (0.45 mL, 3.1 mmol) were heated at 150 °C for 5 days. Flash chromatography (1:3 EtOAc–hexane) gave **11**: 66 mg (54%, based on recovered **9**); pale yellow oil; IR (CCl_4) 3070 (w), 3050 (w), 3010 (w), 1720 (vs), 1145 (s); ^1H NMR ($CDCl_3$) 7.31 (m, 5), 3.97 (d, 1, J = 13.3), 3.81 (d, 1, J = 13.3), 3.70 (s, 3), 3.70 (m, 1), 3.00 (m, 2), 2.70 (m, 2), 2.17 (m, 1), 1.40 (s, 9); mass spectrum, m/z (relative intensity) 405 (M^+, 6), 332 (70), 304 (26), 276 (82), 91 (100).

Pyrrolidines 12a and 12b. Aziridine **9** (93 mg, 0.49 mmol), (*E*)-enone iv (302 mg, 1.32 mmol), and xylene were heated at 175

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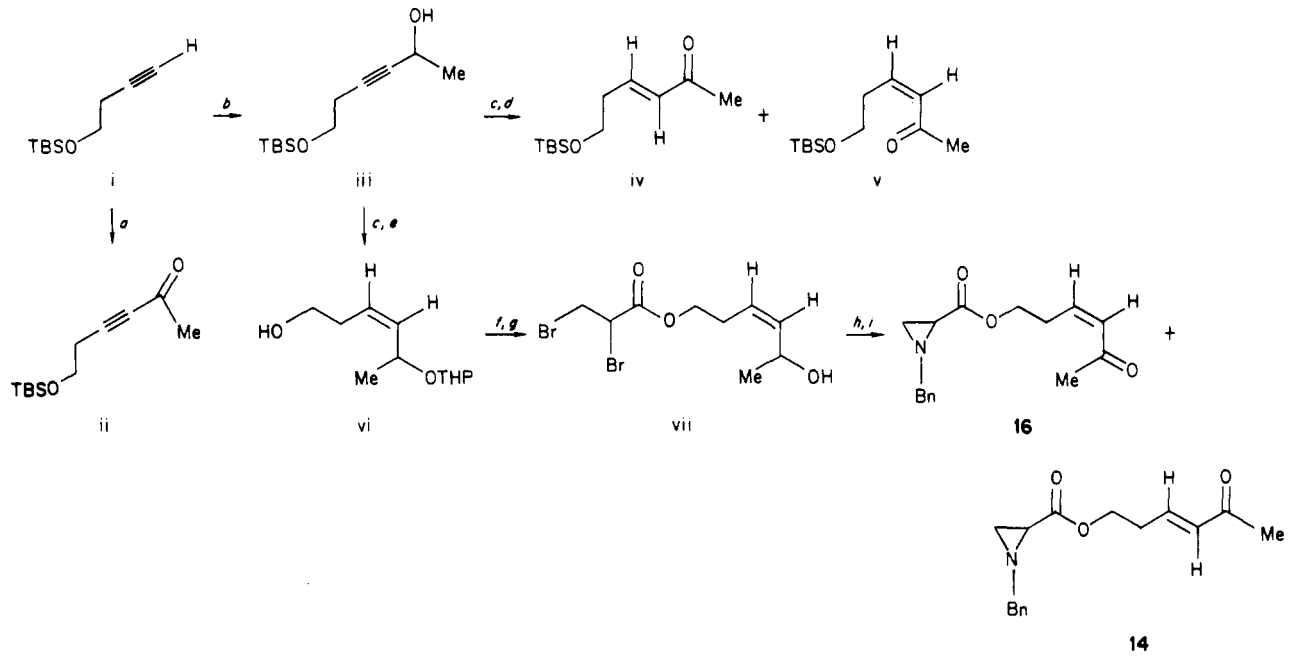
Scheme III[a]



[a] (*a*) MeLi, 0 °C; MeCON(OMe)Me, 0–66 °C, 3 h. (*b*) MeLi, 0 °C; MeCHO, 0 °C to room temperature, 3.5 h. (*c*) 5% Pd/$BaSO_4$, H_2. (*d*) PDC, 18 h. (*e*) DHP, PPTS; $(n\text{-Bu})_4NF$, 0 °C to room temperature, 1 h. (*f*) $BrCH_2CH(Br)COCl$, $KHCO_3$, 15 h. (*g*) PPTS, EtOH. (*h*) $BnNH_2$, $2Et_3N$, 60 °C, 18 h. (*i*) PDC, 14 h.

°C for 2 days. Flash chromatography (1:3 Et_2O–hexane) gave **12b** (high R_f isomer): 114 mg (56%); colorless oil; IR (CCl_4) 1735 (s), 1715 (s), 1240 (s), 1190 (s), 1165 (s), 1080 (vs); ^1H NMR ($CDCl_3$) 7.29 (m, 5), 3.99 (d, 1, J = 13.1), 3.68 (s, 3), 3.63 (m, 3), 3.55 (d, 1, J = 13.1), 3.07 (dd, 1, J = 5.3, 5.6), 2.75 (dd, 1, J = 4.2, 9.3), 2.62 (dd, 1, J = 7.0, 9.3), 2.41 (m, 1), 2.23 (s, 3), 1.74 (m, 2), 0.85 (s, 9), 0.00 (s, 6); mass spectrum (CI, CH_4), m/z (relative intensity) 420 (M + 1^+, 100); mass spectrum m/z 419.2492 (M^+, calcd for $C_{23}H_{37}NO_3Si$ 419.2492). **12a** (low R_f isomer): 10 mg (5%); colorless oil; IR (CCl_4) 1745 (s), 1730 (s), 1715 (s), 1180 (s), 1160 (s), 1075 (vs); ^1H NMR ($CDCl_3$) 7.27 (m, 5), 3.87 (d, 1, J = 13.1), 3.64 (m, 2), 3.62 (s, 3), 3.52 (t, 2, J = 6.2), 3.17 (t, 1, J = 8.2), 3.06 (t, 1, J = 8.6), 2.71 (m, 1), 2.60 (m, 1), 2.15 (s, 3), 1.60 (m, 2), 0.81 (s, 9), –0.04 (s, 6); mass spectrum (CI, $i\text{-}C_4H_{10}$), m/z (relative intensity) 420 (M + 1^+, 100), 404 (10), 362 (16), 288 (87).

Pyrrole 13. Aziridine **9** (55 mg, 0.29 mmol), ynone ii (172 mg, 0.76 mmol), and xylene were heated at 175 °C for 36 h. Flash chromatography (3:7 Et_2O–hexane) gave **13**: 27 mg (22%); IR (CCl_4) 1740 (m), 1705 (s), 1675 (s), 1235 (s), 1080 (vs); ^1H NMR ($CDCl_3$) 7.22 (m, 6), 5.52 (s, 2), 3.80 (s, 3), 3.78 (m, 2), 3.39 (t, 2, J = 7.0), 2.39 (s, 3), 0.86 (s, 9), –0.03 (s, 6); mass spectrum (CI, CH_4), m/z (relative intensity) 416 (M + 1^+, 100), 400 (41), 358 (92), 284 (70).

General Procedure for the Preparation of 1,2-Dibromopropionic Esters. Under argon, a solution of 15–30 mmol of the alcohol in 5 mL of THF was added dropwise to 2,3-dibromopropionyl chloride cooled by an ice–H_2O bath. After 0.5 h, the solvent was evaporated and excess alcohol was removed by distillation. The dibromo esters were purified by vacuum distillation.

Preparation of Aziridines 14 and 16. Aziridines **14** and **16** were prepared according to Scheme III.

Ynol iii. A stirring solution of 1.35 g (7.32 mmol) of the silyl ether of 3-butyn-1-ol i in 80 mL of THF under argon was cooled to 0 °C, followed by slow, dropwise addition of 5.42 mL (7.32 mmol) of 1.35 M methyllithium in ether. A solution of 0.50 mL (8.9 mmol) of distilled acetaldehyde in 40 mL of THF was then added dropwise. The reaction mixture was allowed to warm to room temperature over 1.5 h and stirred at room temperature for 2 h. Then the reaction mixture was quenched with 75 mL of water and reduced to two-thirds the original volume by evaporation. This solution was saturated with NaCl and extracted with ether (2 × 100 mL). The combined organic extracts were dried over $MgSO_4$ and filtered and the solvent was removed by evaporation to give 1.68 g of a gold oil. Purification by bulb-to-bulb distillation gave ynol iii: 1.53 g (92%); pale yellow oil; bp 110–118 °C (0.2 mm); IR (film) 3380 (br m), 2235 (w), 1090 (vs), 820 (vs), 755 (s); ^1H NMR ($CDCl_3$) 4.40 (m, 1), 3.60 (t, 2, J = 7), 2.40 (br s, 1, D_2O exchangable), 2.30 (dt, 2, J = 2, 7), 1.30 (d, 3, J = 7), 0.85 (s, 9), 0.00 (s, 6); mass spectrum, m/z (relative intensity) 171 (29), 153 (25), 105 (66), 75 (100).

Alcohol vi. To a stirring solution of 1.64 g (7.18 mmol) of ynol iii in 20 mL of methanol and 10 mL of pyridine in a hydrogenation vessel was added 82 mg (5% w/w) 5% Pd/$BaSO_4$. The apparatus was evacuated and repeatedly flushed with hydrogen. After uptake of 1 equiv of hydrogen (183 mL), the reaction mixture was filtered through a pad of Celite and concentrated in vacuo. Purification by bulb-to-bulb distillation gave the allylic alcohol: 1.56 g (95%); colorless oil; bp 73–78 °C (0.01 mm); IR (film) 3470 (br m), 1080 (vs), 820 (vs), 755 (s); ^1H NMR ($CDCl_3$) 5.40 (m, 2), 4.50 (quintet, 1, J = 6), 3.60 (t, 2, J = 6), 2.30 (m, 3), 1.15 (d, 3, J = 6), 0.85 (s, 9), 0.00 (s, 6); mass spectrum, m/z (relative intensity) 230 (M^+, 0.1), 173 (17), 105 (87), 75 (100).

The Grieco[19] procedure was followed with 5.00 g (21.7 mmol) of the purified allylic alcohol, 3.65 g (43.4 mmol) of distilled dihydropyran, and 545 mg (2.17 mmol) of pyridinium *p*-toluenesulfonate. Purification of the product by bulb-to-bulb distillation gave the allylic THP ether: 6.82 g (100%); colorless liquid; IR (film) 2940 (s), 1090 (m), 1065 (m), 1015 (m), 1000 (m), 760 (vs); ^1H NMR ($CDCl_3$) 5.25 (m, 2), 4.45 (m, 2), 3.55 (t, 4, J = 6), 2.25 (q, 2, J = 6), 1.50 (m, 6), 1.15 (2 d, 3, J = 6), 0.85 (s, 9), 0.00 (s, 6); mass spectrum, m/z (relative intensity) 243 (2), 213 (2), 199 (1), 101 (9), 85 (100).

A stirring solution of 6.82 g (21.7 mmol) of the allylic THP ether in 50 mL of THF under argon was cooled to 0 °C and (27.0 mmol) of 1.00 M tetra-*n*-butylammonium fluoride in THF was added dropwise. The reaction mixture was stirred at 0 °C for 1 h and then allowed to warm to room temperature. A 50-mL portion of 1:1 ether–hexane was added and the solution was washed with 75 mL of brine. The brine was extracted with 75 mL of ether. The combined organic layers were dried over $MgSO_4$ and filtered and the solvent was removed by evaporation to give 8.30 g of a mixture of alcohol vi and *tert*-butyldimethylsilyl fluoride. Flash column chromatography (1:3 ethyl acetate–hexane) gave alcohol vi: 3.78 g (87%); colorless liquid; bp 90–95 °C (bulb-to-bulb distillation, 0.10 mm); IR (film) 3420 (br m), 3010 (w), 2940 (s), 1115 (s), 1100 (s), 1060 (vs); ^1H NMR ($CDCl_3$) 5.35 (m, 2), 4.60 (m, 2), 3.55 (t, 4, J = 7), 3.80 (br s, 1), 2.25 (m, 2), 1.55 (m, 6), 1.20 (2 d, 3, J = 6); mass spectrum, m/z (relative intensity) 200

(M^+, 0.3), 116 (3), 101 (11), 99 (40), 85 (100). 0.14 g (2%) of allylic THP ether was recovered.

Dibromo Ester vii. Under argon, a solution of 7.91 g (31.6 mmol) of 2,3-dibromopropionyl chloride in 10 mL of THF was added dropwise to a stirring suspension of 6.33 g (31.6 mmol) of alcohol vi and 7.40 g (74.0 mmol) of $KHCO_3$ in 20 mL of THF. After 15 h, the reaction mixture was filtered, washed with H_2O (50 mL) and brine (50 mL), dried ($MgSO_4$), and concentrated in vacuo. Flash column chromatography (1:3 EtOAc–hexane) gave two diastereomers of allylic THP ether dibromo ester:[21] 8.71 g (67%); colorless oil; bp 120–125 °C (0.06 mm, bulb-to-bulb distillation); (high R_f diastereomer) IR (film) 2940 (m), 1745 (vs), 1135 (m), 1060 (m), 1015 (s); ^1H NMR ($CDCl_3$) 5.44 (m, 2), 4.63 (dt, 1, J = 6.4, 10.0), 4.55 (m, 1), 4.42 (dd, 1, J = 4.5, 11.3), 4.24 (t, 2, J = 6.8), 3.90 (dd, 1, J = 9.9, 11.3), 3.85 (m, 1), 3.65 (dd, 1, J = 4.5, 9.9), 3.46 (m, 1), 2.49 (ddt, 2, J = 1.4, 6.8, 6.9), 1.72 (m, 2), 1.51 (m, 4), 1.25 (d, 3, J = 6.4); mass spectrum, m/z (relative intensity) 315 (4), 313 (7), 311 (M^+, 4), 189 (1.5), 187 (3), 185 (1.5), 85 (88), 81 (100). Dibromo ester[21] vii: 1.95 g (19%); colorless oil; IR (CCl_4) 3620 (w), 1755 (vs), 1240 (s), 1190 (s), 1130 (s); ^1H NMR ($CDCl_3$) 5.55 (m, 2), 4.45 (m, 4), 3.75 (m, 2), 3.30 (br s, 1, D_2O exchangeable), 2.55 (m, 2), 1.30 (d, 3, J = 6); mass spectrum (CI, CH_4), m/z (relative intensity) 315 (48), 313 (100), 311 (52).

The allylic THP ether dibromo ester was converted to dibromo ester vii in 85% yield by deprotection following the Grieco[19] method.

Aziridines 14 and 16. Under argon, a mixture of 0.22 mL (2.0 mmol) of benzylamine and 0.56 mL (4.0 mmol) of triethylamine in 15 mL of toluene was added dropwise to a stirring 0 °C solution of 665 mg (2.0 mmol) dibromo ester vii in 25 mL of toluene. After 0.5 h, the reaction mixture was warmed to 60 °C. The reaction mixture was allowed to cool after 18 h, diluted with ether, filtered through Celite, and concentrated in vacuo. Flash column chromatography (1:1 EtOAc–hexane) gave (*Z*)-allylic alcohol aziridine, as a mixture of diastereomers: 498 mg (90%); pale yellow oil; IR (CCl_4) 3620 (w), 3370 (br w), 1740 (vs), 1285 (s), 1170 (s), 1060 (s); ^1H NMR ($CDCl_3$) 7.25 (m, 5), 5.56 (m, 1), 5.33 (m, 1), 4.58 (m, 1), 4.08 (m, 2), 3.70 (2 d, 1, J = 13.4), 3.35 (2 d, 1, J = 13.4), 2.56 (m, 1), 2.23 (m, 3), 1.75 (m, 1), 1.31 (m, 1), 1.21 (2 d, 3, J = 6.2); mass spectrum (CI, CH_4), m/z (relative intensity) 276 (M + 1^+, 93), 258 (100), 206 (44), 178 (82).

Under nitrogen, a solution of 113 mg (0.41 mmol) of (*Z*)-allylic alcohol aziridine in 2 mL of CH_2Cl_2 was added dropwise to a stirring suspension of 235 mg (0.62 mmol) of pyridinium dichromate in 3 mL of CH_2Cl_2. The reaction mixture was diluted with 5 mL of ether after 14 h and filtered through Celite, and the solvent evaporated. Flash column chromatography (1:1 EtOAc–hexane) gave aziridine **16**: 64 mg (57%); colorless oil; IR (CCl_4) 3070 (w), 3035 (w), 1755 (s), 1740 (s), 1700 (m), 1170 (vs); ^1H NMR ($CDCl_3$) 7.29 (m, 5), 6.22 (dt, 1, J = 1.6, 11.4), 6.02 (dt, 1, J = 6.9, 11.4), 4.21 (dt, 2, J = 5.2, 6.5), 3.54 (A of ABq, 1, J = 13.5), 3.52 (B of ABq, 1, J = 13.5), 2.95 (ddt, 2, J = 1.6, 6.5, 6.9), 2.22 (m, 2), 2.19 (s, 3), 1.74 (dd, 1, J = 1.1, 6.3); mass spectrum (CI, CH_4), m/z (relative intensity) 274 (M + 1^+, 100), 206 (7), 178 (47). Aziridine **14**: 14 mg (12%); colorless oil; IR (CCl_4) 3065 (w), 3035 (w), 1755 (s), 1740 (s), 1685 (s), 1635 (w), 1170 (vs); ^1H NMR ($CDCl_3$) 7.28 (m, 5), 6.70 (dt, 1, J = 6.8, 16.0), 6.10 (dt, 1, J = 1.4, 16.0), 4.24 (dt, 2, J = 4.8, 6.4), 3.57 (A of ABq, 1, J = 13.5), 3.48 (B of ABq, 1, J = 13.5), 2.55 (ddt, 2, J = 1.4, 6.4, 6.8), 2.22 (s, 3), 2.20 (m, 2), 1.75 (dd, 1, J = 1.1, 6.3); mass spectrum (CI, CH_4), m/z (relative intensity) 274 (M + 1^+, 100), 178 (20).

Ynone ii. Under argon, 3.83 mL (5.75 mmol) of 1.50 M methyllithium in ether was added dropwise (15 min) to a stirring 0 °C solution of the silyl ether of 3-butyn-1-ol i in 60 mL of THF. A solution of 840 mg (8.15 mmol) of *N*-methoxy-*N*-methylacetamide[22] in 25 mL of THF was then added dropwise. The reaction mixture was allowed to warm to room temperature over 1 h and refluxed for 2 h. The reaction mixture was washed with 20 mL of 4% aqueous HCl and 20 mL of brine. The combined aqueous washings were neutralized with aqueous NaOH, saturated with NaCl, and extracted with 40 mL of CH_2Cl_2. The combined organic layers were dried over $MgSO_4$, filtered, and concentrated in vacuo to give 1.39 g of a liquid. Purification by bulb-to-bulb distillation gave ynone ii: 1.04 g (80%); colorless liquid; IR (CCl_4) 2180 (s), 1680 (vs), 1210 (s), 1090 (br vs), 755 (br m); ^1H NMR ($CDCl_3$) 3.70 (t, 2, J = 7), 2.45 (t, 2, J = 7), 2.20 (s, 3), 0.80 (s, 9), 0.00 (s, 6); mass spectrum, m/z (relative intensity) 211 (12), 196 (1), 181 (4), 169 (47), 139 (100).

(*E*)- and (*Z*)-Enones iv and v. Under argon, a solution of 2.31 g (10.0 mmol) of the allylic alcohol, from hydrogenation of ynol iii, in 15 mL of CH_2Cl_2 was added dropwise to a stirring suspension of 5.17 g (13.7 mmol) of pyridinium dichromate in 25 mL of CH_2Cl_2. After 18 h, the reaction mixture was diluted with Et_2O, filtered through Celite, and concentrated in vacuo. Flash column chromatography (1:4 Et_2O–hexane) gave high R_f (*Z*)-enone v: 1.37 g (60%); colorless liquid; IR (film) 1690 (s), 1630 (m), 1615 (m), 1080 (vs), 815 (vs), 755 (s); ^1H NMR (CCl_4) 6.10 (m, 1), 6.05 (s, 1), 3.65 (t, 2, J = 6), 2.70 (dt, 2, J = 5, 6), 2.00 (s, 3), 0.85 (s, 9), 0.00 (s, 6); mass spectrum, m/z (relative intensity) 228 (M^+, 0.06), 213 (4), 198 (3), 171 (100), 141 (43). Low R_f (*E*)-enone iv: 0.70 g (30%); colorless liquid; IR (film) 1700 (m), 1680 (s), 1630 (m), 1080 (vs), 815 (vs), 755 (s); ^1H NMR (CCl_4) 6.60 (dt, 1, J = 7, 16), 5.90 (d, 1, J = 16), 3.65 (t, 2, J = 6), 2.35 (q, 2, J = 6), 2.05 (s, 3), 0.85 (s, 9), 0.00 (s, 6); mass spectrum, m/z (relative intensity) 227 (M – 1^+, 0.1), 213 (3), 198 (5), 171 (95), 141 (100).

General Procedure for the Preparation of *N*-Benzylaziridines from 1,2-Dibromopropionic Esters. This procedure is a modification of that described by Stolberg.[15] Under argon, a mixture of 20 mmol of triethylamine and 10 mmol of benzylamine in 10 mL of toluene was added dropwise to a stirring solution of 10 mmol of dibromo ester in 30 mL of toluene at 0 °C. After warming to room temperature over 1 h, the reaction mixture was heated at 60 °C until aziridine formation was complete (2–18 h). Upon cooling, the reaction mixture was diluted with ether and filtered through Celite. The filtrate was washed with H_2O (20 mL) and brine (20 mL), dried over $MgSO_4$, and concentrated in vacuo. Purification of the aziridine was achieved by flash chromatography on silica or vacuum distillation.

Aziridine 19: bp 116–120 °C (0.03 mm); 89%; IR (film) 1750 (vs), 1650 (w), 1610 (w), 1180 (vs), 1010 (m); ^1H NMR ($CDCl_3$) 7.32 (m, 5), 5.92 (ddt, 1, J = 5.8, 10.3, 17.1), 5.30 (dq, 1, J = 1.4, 17.1), 5.23 (dq, 1, J = 1.4, 10.3), 4.64 (dq, 2, J = 1.4, 5.8), 3.56 (A of ABq, 1, J = 13.5), 3.55 (B of ABq, 1, J = 13.5), 2.29 (dd, 1, J = 1.2, 3.2), 2.23 (dd, 1, J = 3.2, 6.4), 1.77 (dd, 1, J = 1.2, 6.4); mass spectrum (CI, CH_4), m/z (relative intensity) 218 (M + 1^+, 29), 176 (57), 132 (73), 91 (100).

Aziridine 21: bp 118–122 °C (0.05 mm); 100%; IR (film) 2080 (s), 3040 (w), 1750 (vs), 1735 (vs), 1650 (w), 1185 (vs); ^1H NMR ($CDCl_3$) 7.29 (m, 5), 5.76 (ddt, 1, J = 6.6, 10.2, 17.1), 5.08 (ddt, 1, J = 1.2, 9.1, 17.1), 5.06 (ddt, 1, J = 1.2, 9.1, 10.2), 4.18 (q, 2, J = 6.7), 3.59 (A of ABq, 1, J = 13.5), 3.50 (B of ABq, 1, J = 13.5), 2.39 (tq, 2, J = 1.3, 6.7), 2.26 (dd, 1, J = 1.2, 3.2), 2.19 (dd, 1, J = 3.2, 6.4), 1.74 (dd, 1, J = 1.2, 6.4); mass spectrum (CI, CH_4), m/z (relative intensity) 232 (M + 1^+, 7), 176 (6), 132 (22), 91 (100).

Aziridine 23. In a hydrogenation apparatus, 4 mg of 5% $Pd/BaSO_4$ was added to a solution of 210 mg (0.82 mmol) of aziridine **33** in 10 mL of 1:1 MeOH–pyridine. The apparatus was flushed repeatedly with hydrogen. After the theoretical uptake of hydrogen, the reaction mixture was filtered and the filtrate concentrated in vacuo. Purification by bulb-to-bulb distillation gave aziridine **23**: 192 mg (91%); colorless oil; bp 137–141 °C (0.02 mm); IR (film) 3070 (w), 3040 (w), 3020 (w), 1750 (vs), 1735 (s), 1180 (vs); ^1H NMR ($CDCl_3$) 7.32 (m, 5), 5.39 (m, 2), 4.13 (q, 2, J = 6.8), 3.55 (s, 2), 2.37 (ddq, 2, J = 1.0, 6.4, 6.8), 2.26 (dd, 1, J = 1.2, 3.0), 2.19 (dd, 1, J = 3.0, 6.3), 2.01 (dq, 2, J = 1.0, 7.2), 1.75 (dd, 1, J = 1.2, 6.3), 0.96 (t, 3, J = 7.5); mass spectrum (CI, CH_4), m/z (relative intensity) 260 (M + 1^+, 100), 176 (37), 160 (7), 132 (17).

Aziridine 25: bp 162–168 °C (0.3 mm); 80%; IR (film) 3085 (w), 3065 (w), 3030 (w), 1750 (s), 1735 (s), 1170 (s); ^1H NMR ($CDCl_3$) 7.31 (m, 5), 5.56 (dtt, 1, J = 1.1, 6.1, 15.3), 5.34 (dtt, 1, J = 1.2, 6.7, 15.3), 4.14 (q, 2, J = 7.0), 3.60 (A of ABq, 1, J = 13.5), 3.51 (B of ABq, 1, J = 13.5), 2.33 (dq, 2, J = 1.1, 6.7), 2.26 (dd, 1, J = 1.2, 3.2), 2.20 (dd, 1, J = 3.2, 6.4), 2.02 (ddq, 2, J = 1.2,

(21) Small quantities of the corresponding α-bromoacrylate may also be produced. This does not decrease the overall yield as α-bromoacrylates are also converted to aziridine under the same conditions as the dibromo esters.

(22) Oster, T.; Harris, T. *Tetrahedron Lett.* **1983**, *24*, 1851. Nahm, S.; Weinreb, S. M. *Ibid.* **1981**, *22*, 3815.

6.1, 7.4), 1.75 (dd, 1, J = 1.2, 6.4), 0.96 (t, 3, J = 7.4); mass spectrum (CI, CH_4), m/z (relative intensity) 260 (M + 1^+, 100), 206 (16), 178 (68).

Aziridine 27: bp 140–145 °C (0.02 mm); 87%; IR (film) 3290 (m), 2090 (w), 1750 (vs), 1275 (m), 1170 (vs); ^{1}H NMR ($CDCl_3$) 7.30 (s, 5), 4.70 (d, 2, J = 3), 3.50 (s, 2), 2.45 (t, 1, J = 3), 2.20 (m, 2), 1.75 (dd, 1, J = 3, 5); mass spectrum (CI, CH_4), m/z (relative intensity) 216 (M + 1^+, 100), 176 (9), 138 (21), 132 (54).

Aziridine 31: bp 145–153 °C (0.03 mm); 100%; IR (CCl_4) 3310 (w), 3060 (w), 3025 (w), 1730 (s), 1165 (vs); ^{1}H NMR ($CDCl_3$) 7.30 (s, 5), 4.20 (t, 2, J = 7), 3.55 (s, 2), 2.55 (dt, 2, J = 3, 7), 2.30 (m, 2), 2.00 (t, 1, J = 3)e, 1.75 (dd, 1, J = 2, 5); mass spectrum (CI, CH_4), m/z (relative intensity) 230 (M + 1^+, 100).

Aziridine 33: bp 127–130 °C (0.01 mm); 100%; IR (CCl_4) 3060 (w), 3030 (w), 1755 (s), 1735 (s), 1165 (vs), 1065 (m); ^{1}H NMR ($CDCl_3$) 7.30 (m, 5), 4.20 (t, 2, J = 7), 3.55 (s, 2), 2.50 (tt, 2, J = 2, 7), 2.25 (dd, 1, J = 1, 3), 2.20 (dd, 1, J = 3, 6), 2.15 (tq, 2, J = 2, 7), 1.75 (dd, 1, J = 1, 6), 1.10 (t, 3, J = 7); mass spectrum (CI, CH_4), m/z (relative intensity) 258 (M + 1^+, 66), 228 (8), 91 (100), 81 (38).

General Procedure for the Flash Vacuum Pyrolysis of Aziridines. The apparatus used and the procedure followed was that of Fowler[16] for nonvolatile compounds. In this procedure, a solution of 100–150 mg (ca. 0.40–0.60 mmol) of aziridine in 3 mL of benzene was subjected to flash vacuum pyrolysis at 300–400 °C. The reaction mixture was concentrated in vacuo and purified by flash chromatography.

FVP of Aziridine 14 (330 °C; 80%). Pyrrolidine **15**: IR (CCl_4) 1755 (vs), 1720 (vs), 1260 (s), 1170 (s), 1055 (s); ^{1}H NMR ($CDCl_3$) 7.28 (m, 5), 4.57 (ddd, 1, J = 2.5, 8.7, 11.1), 4.29 (d, 1, J = 13.2), 4.24 (m, 1), 3.41 (d, 1, J = 13.2), 3.33 (d, 1, J = 9.8), 3.23 (dd, 1, J = 7.0, 8.7), 3.02 (m, 1), 2.89 (ddd, 1, J = 6.9, 7.5, 10.3), 2.27 (dd, 1, J = 6.8, 10.2), 2.12 (s, 3), 2.11 (m, 1), 1.59 (m, 1); mass spectrum (CI, CH_4), m/z (relative intensity) 274 (M + 1^+, 100); mass spectrum, m/z 273.1364 (M^+, calcd for $C_{16}H_{19}NO_3$ 273.1365).

FVP of Aziridine 16 (285 °C; 52% total). Pyrrolidine **18**: IR (CCl_4) 1750 (vs), 1720 (s), 1055 (s); ^{1}H NMR ($CDCl_3$) 7.23 (m, 5), 4.55 (ddd, 1, J = 3.8, 4.1, 10.8), 4.21 (d, 1, J = 13.7), 4.12 (ddd, 1, J = 3.7, 4.1, 11.1), 3.50 (d, 1, J = 13.7), 3.40 (d, 1, J = 7.4), 3.18 (m, 2), 2.94 (quintet, 1, J = 7.5), 2.50 (dt, 1, J = 1.0, 7.6), 2.09 (s, 3), 1.72 (m, 2); mass spectrum (CI, i-C_4H_{10}), m/z (relative intensity) 274 (M + 1^+, 100); mass spectrum, m/z 273.1373 (M^+, calcd for $C_{16}H_{19}NO_3$ 273.1365). Pyrrolidine **17**: IR (CCl_4) 1775 (vs), 1720 (s), 1115 (s), 1100 (s); ^{1}H NMR ($CDCl_3$) 7.34 (m, 5), 4.59 (d, 1, J = 12.5), 4.38 (t, 2, J = 6.7), 3.44 (d, 1, J = 12.5), 3.33 (d, 1, J = 12.3), 3.27 (m, 2), 2.62 (dd, 1, J = 3.6, 10.1), 2.56 (m, 1), 2.19 (s, 3), 2.14 (m, 1), 1.90 (dt, 1, J = 6.4, 1.1); mass spectrum (CI, i-C_4H_{10}), m/z (relative intensity) 274 (M + 1^+, 100), 246 (18); mass spectrum, m/z 273.1361 (M^+, calcd for $C_{16}H_{19}NO_3$ 273.1365).

FVP of Aziridine 19 (320 °C; 67%). Pyrrolidine **20**: IR (CCl_4) 3085 (w), 3065 (w), 3035 (w), 1780 (vs), 1170 (s), 1000 (s); ^{1}H NMR ($CDCl_3$) 7.31 (m, 5), 4.44 (dd, 1, J = 8.1, 9.2), 4.18 (d, 1, J = 13.2), 4.12 (dd, 1, J = 4.4, 9.2), 3.78 (d, 1, J = 13.2), 3.48 (d, 1, J = 8.4), 3.10 (dtt, 1, J = 4.3, 4.7, 8.4), 2.84 (m, 1), 2.61 (dt, 1, J = 7.2, 9.3), 2.14 (m, 1), 1.72 (m, 1); mass spectrum (CI, CH_4), m/z (relative intensity) 218 (M + 1^+, 100), 190 (22), 173 (5), 159 (10), 91 (14). Anal. Calcd for $C_{13}H_{15}NO_2$: C, 71.87; H, 6.96; N, 6.45. Found: C, 71.58; H, 7.21; N, 6.31.

FVP of Aziridine 21 (330 °C; 69%). Pyrrolidine **22**: IR (CCl_4) 3085 (w), 3065 (w), 3035 (w), 1750 (s), 1060 (s); ^{1}H NMR ($CDCl_3$) 7.29 (m, 5), 4.65 (ddd, 1, J = 2.3, 9.9, 12.1), 4.27 (d, 1, J = 13.2), 4.22 (m, 1), 3.39 (d, 1, J = 13.2), 3.19 (d, 1, J = 9.6), 2.97 (dd, 1, J = 7.0, 8.1), 2.70 (m, 1), 2.22 (m, 3), 1.57 (m, 2); mass spectrum (CI, CH_4), m/z (relative intensity) 232 (M + 1^+, 20), 173 (7), 159 (91), 91 (100); mass spectrum, m/z 231.1251 (M^+, calcd for $C_{14}H_{17}NO_2$ 231.1259).

FVP of Aziridine 23 (330 °C; 16%). Pyrrolidine **24**: IR (CCl_4) 3090 (w), 3070 (w), 3035 (w), 1750 (vs), 1065 (s); ^{1}H NMR ($CDCl_3$) 7.30 (m, 5), 4.58 (ddd, 1, J = 4.1, 5.6, 10.8), 4.30 (d, 1, J = 13.6), 4.20 (m, 1), 3.60 (d, 1, J = 13.6), 3.43 (d, 1, J = 7.2), 2.65 (m, 3), 2.09 (q, 1, J = 7.0), 1.81 (m, 2), 1.34 (q, 2, J = 7.3, 0.86 (t, 3, J = 7.3); mass spectrum (CI, CH_4), m/z (relative intensity) 260 (M + 1^+, 100), 230 (8), 91 (61); mass spectrum, m/z 259.1566 (M^+, calcd for $C_{16}H_{21}NO_2$ 259.1572).

FVP of Aziridine 25 (330 °C; 26%). Pyrrolidine **26**: IR (CCl_4) 3090 (w), 3065 (w), 3030 (w), 1745 (vs), 1255 (s), 1065 (s); ^{1}H NMR ($CDCl_3$) 7.28 (m, 5), 4.65 (dt, 1, J = 2.3, 9.7), 4.24 (d, 1, J = 13.3), 4.19 (m, 1), 3.35 (d, 1, J = 13.3), 3.25 (d, 1, J = 9.6), 3.08 (dd, 1, J = 5.2, 7.8), 2.22 (m, 2), 2.06 (m, 1), 1.82 (m, 2), 1.54 (m, 2), 1.33 (m, 1), 0.87 (t, 3, J = 7.3); mass spectrum (CI, CH_4), m/z (relative intensity) 260 (M + 1^+, 100), 232 (7), 187 (27), 182 (12), 168 (10), 158 (18); mass spectrum, m/z 259.1580 (M^+, calcd for $C_{16}H_{21}NO_2$ 259.1572).

FVP of Aziridine 27 (320 °C; 46%). 2,5-Dihydropyrrole **28** (35%): IR (CCl_4) 3090 (w), 3070 (w), 3035 (w), 1805 (vs), 1120 (s), 1075 (s); ^{1}H NMR ($CDCl_3$) 7.31 (m, 5), 5.84 (dd, 1, J = 1.0, 1.4), 4.81 (s, 2), 4.40 (d, 1, J = 12.8), 4.27 (m, 1), 3.75 (m, 1), 3.71 (d, 1, J = 12.8), 3.55 (m, 1); mass spectrum (CI, CH_4), m/z (relative intensity) 216 (M + 1^+, 15), 188 (11), 171 (99), 91 (100). Pyrrole **29** (8%): IR (CCl_4) 3115 (w), 3090 (w), 3060 (w), 3035 (w), 1760 (vs), 1035 (s), 1000 (s); ^{1}H NMR ($CDCl_3$) 7.32 (m, 5), 6.98 (d, 1, J = 2.5), 6.10 (d, 1, J = 2.5), 5.26 (s, 2), 5.11 (s, 2); mass spectrum (CI, CH_4), m/z (relative intensity) 213 (M + 1^+, 100), 91 (24); mass spectrum, m/z 213.0795 (M^+, calcd $C_{13}H_{11}NO_2$ 213.0790). Pyrrole **30** (3%): IR (CCl_4) 3100 (w), 3080 (w), 3040 (w), 3020 (w), 1260 (s), 1080 (vs), 1000 (vs); ^{1}H NMR ($CDCl_3$) 8.53 (d, 1, J = 1.9), 7.93 (dd, 2, J = 1.9, 6.5), 7.61 (m, 2), 7.46 (m, 3), 2.39 (s, 3); mass spectrum, m/z (relative intensity) 169 (M^+, 100), 154 (18), 141 (31), 115 (47), 91 (17), 77 (18); mass spectrum, m/z 169.0892 (M^+, calcd for $C_{12}H_{11}N$ 169.0891).

Conversion of 28 and 29 to Pyrrole 30 by NiO_2. After flash vacuum pyrolysis of 60 mg (0.28 mmol) of aziridine **27**, the reaction mixture was transferred to a flask containing 480 mg (1.4 mmol) of NiO_2[18] and 5 mL of benzene under argon. The suspension was refluxed 16 h, allowed to cool, filtered through Celite, and concentrated in vacuo. Filtration through a pad of silica gel (hexane to ether–hexane) and removal of the solvent in vacuo gave 18.5 mg (40%) of tricyclic pyrrole **30**.

FVP of Aziridine 31 (300 °C; 63%). Pyrrole **32**: IR (CCl_4) 3060 (w), 3020 (w), 1715 (vs), 1065 (m); ^{1}H NMR ($CDCl_3$) 7.23 (m, 5), 6.79 (d, 1, J = 2.5), 5.96 (d, 1, J = 2.5), 5.48 (s, 2), 4.45 (t, 2, J = 6.1), 2.86 (t, 2, J = 6.1); mass spectrum (CI, CH_4), m/z (relative intensity) 228 (M + 1^+, 100). Anal. Calcd for $C_{14}H_{13}NO_2$: C, 73.99; H, 5.77; N, 6.16. Found: C, 73.65; H, 5.83; N, 6.35.

FVP of Aziridine 33 (300 °C; 34%). Pyrrole **34**: IR (CCl_4) 3085 (w), 3060 (w), 3030 (w), 1720 (s), 1060 (m), 1005 (m); ^{1}H NMR ($CDCl_3$) 7.25 (s, 5), 6.60 (s, 1), 5.40 (s, 2), 4.45 (t, 2, J = 6), 2.75 (t, 2, J = 6), 2.40 (q, 2, J = 8), 1.15 (t, 3, J = 8); mass spectrum (CI, CH_4), m/z (relative intensity) 256 (M + 1^+, 100), 240 (5), 178 (23), 155 (42). Anal. Calcd for $C_{16}H_{17}NO_2$: C, 75.27; H, 6.71; N, 5.49. Found: C, 75.42; H, 6.87; N, 5.14.

Acknowledgment. We thank the National Institutes of Health for generous financial support. We acknowledge numerous helpful discussions with Frank Fowler (SUNY, Stony Brook), Pat Confalone (DuPont), and Steve Weinreb (PSU) during the course of the study. Also, we thank Pat Confalone for a preprint of unpublished results, Joseph J. Perez for furnishing technical assistance, and Robert Minard, Greg Hancock, V. Elango, and Alan Freyer for help in obtaining spectral data.