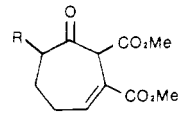
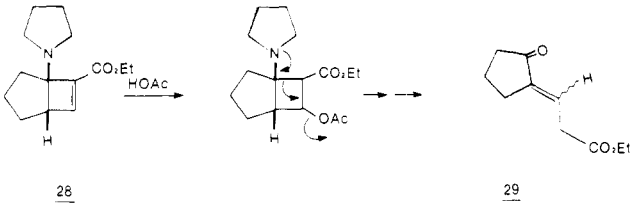
References and Notes

(1) Syntex Postdoctoral Fellow, 1977–1978.
(2) R. D. Clark and K. G. Untch, *J. Org. Chem.*, companion paper, this issue.
(3) Side products from the reaction are recovered ketone and 10–20% carbon silylated ketone.
(4) (a) G. A. Berchtold and G. F. Uhlig, *J. Org. Chem.*, **28**, 1459 (1963); (b) K. C. Brannock, R. D. Burpitt, V. Goodlett, and J. G. Thweatt, *ibid.*, **28**, 1464 (1963); (c) L. A. Paquette and R. W. Begland, *J. Am. Chem. Soc.*, **88**, 4685 (1966); (d) C. F. Huebner, L. Dorfman, M. Robison, E. Donoghue, W. Pierson, and P. Strachan, *J. Org. Chem.*, **28**, 3134 (1963); (e) J. A. Hirsch and F. J. Cross, *ibid.*, **36**, 955 (1971).
(5) Compounds **2** and **7** are apparently very sensitive to subtle changes in reaction conditions. In one instance, treatment of **7** with NaH in *tert*-butyl alcohol did afford the ring expansion product **26** in moderate yield with no detectable amount (TLC) of **20** present. However, this result could not be reproduced subsequently in several attempts. Furthermore, even more puzzling, a sample of **2** stored at room temperature for two weeks rearranged cleanly to **27**.



26 R = CH_3
27 R = H

(6) A similar product was obtained from the corresponding bicyclo[3.2.0]-heptenylpyrrolidinyl compound **28** in ref 4d upon treatment with acetic acid. Our explanation involving initial Michael addition to the cyclobutenyl ester (of acetate in this case) followed by fragmentive elimination may also be invoked to explain formation of this product. This mechanism is also consistent with the finding that **29** was not obtained upon treatment of **28** with aqueous hydrochloric acid since irreversable protonation of the nitrogen rules out the fragmentation.



28 **29**

(7) K. Narasaka, K. Soai, Y. Aikawa, and T. Mukaiyama, *Bull. Chem. Soc. Jpn.*, **49**, 779 (1976).
(8) We have been unable to obtain cycloadducts from reaction of silyl ethers with enones. In this case the products are mainly Michael adducts.

Intramolecular Dipolar Cycloaddition Reactions with Azomethine Ylides

Albert Padwa* and Hao Ku

Department of Chemistry, State University of New York at Buffalo, Buffalo, New York 14214

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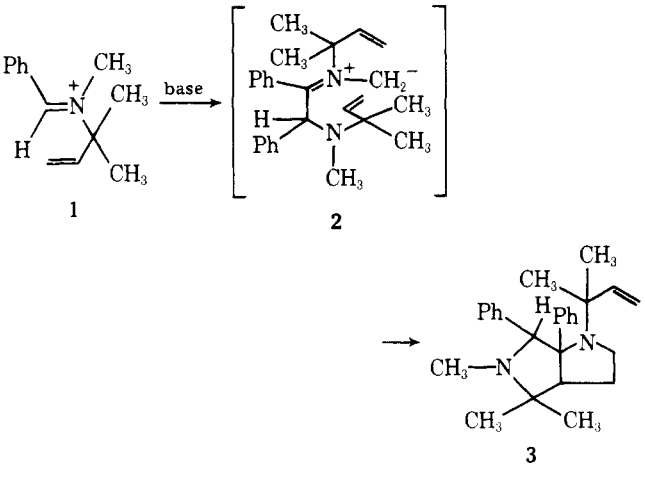
The intramolecular 1,3-dipolar cycloaddition reactions of several aziridine carboxylates containing a neighboring π bond were studied. The only reaction found to occur on thermolysis of *cis*- and *trans*-allyl 1-isopropyl-2-(*p*-biphenyl)-3-aziridinecarboxylate corresponds to isomerization about the three-membered ring. With this system, equilibration of the ring-opened azomethine ylides occurs at a faster rate than internal cycloaddition. Attachment of an electron-withdrawing carbomethoxy substituent to the double bond was found to significantly enhance the intramolecular dipolar cycloaddition rate. Isomerization of the less reactive *cis*-azomethine ylide to the trans form was still found to compete with the cycloaddition reaction. An additional system which was also studied involved the thermal chemistry of *cis*- and *trans*-methyl *N*-(4-carbomethoxy-3-butenyl)-2-(*p*-biphenyl)-3-aziridinecarboxylate. The azomethine ylides derived from these aziridines undergo regioselective cycloadditions which are compatible with the principles of frontier MO theory.

1,3-Dipoles bearing a functional group able to behave as a dipolarophile are extremely interesting substrates. In fact, the intramolecular cycloaddition reaction of a properly functionalized 1,3-dipole represents a general scheme for the synthesis of novel fused ring heterocycles.[1-3] Intramolecular dipolar cycloadditions have been carried out with nitrones,[4-10] diazoalkanes,[11-15] azides,[16-20] azomethine imines,[21,22] carbonyl oxides,[23] nitrile imines,[24,25] nitrile ylides,[26] and sydnones.[27] As part of a program directed toward a study of the scope and generality of intramolecular dipolar cycloaddition reactions, we had the occasion to prepare several aziridine carboxylates containing a π bond in close proximity to the three-membered heterocyclic ring. Reactions involving the thermal and photochemical cleavage of aziridines to azomethine ylides and their subsequent 1,3-dipolar additions to reactive carbon–carbon multiple bonds are well known.[28-36] Huisgen and coworkers have firmly established that the thermal ring cleavage of aziridines involves stereospecific, conrotatory ring opening.[37] On irradiation a disrotatory cleavage of the aziridine ring was observed.[37] Although the bimolecular cycloaddition reactions of the ring-opened valence tautomer of aziridines are well documented, there is only one example in the literature dealing with an intramolecular cycloaddition reaction of an azomethine ylide. Recently, Deyrup and co-workers reported that the reaction of the aldiminium salt **1** with base afforded dimer **3**.[38] The formation of **3** was suggested to arise via the cyclization of a transient 1,3-dipolar azomethine ylide **2**.



1 **2** **3**

In this paper, we wish to describe several of the features associated with the intramolecular dipolar cycloaddition reaction of azomethine ylides which possess a neighboring double bond.

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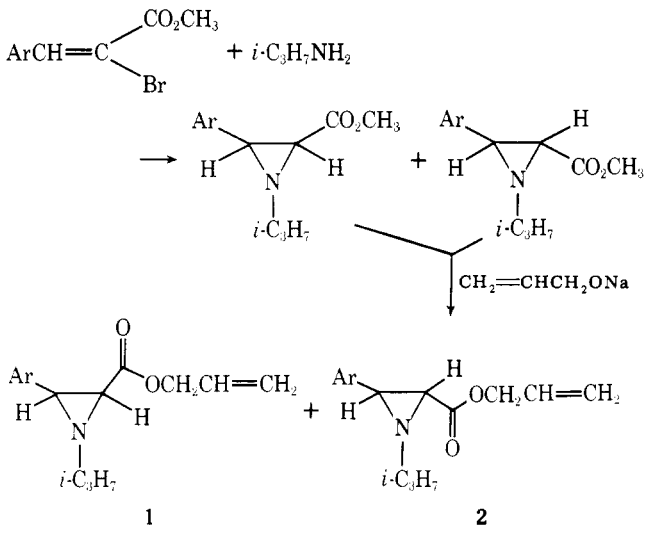
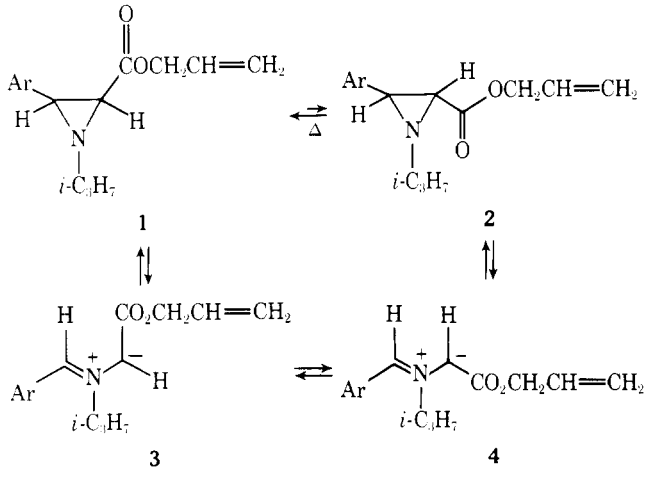
Results and Discussion

As our first model we chose to investigate the thermal chemistry of a series of unsaturated aziridine carboxylates. The aziridine esters **1** and **2** employed in this study were conveniently prepared by the treatment of *cis*- and *trans*-methyl 1-isopropyl-2-(*p*-biphenyl)-3-aziridinecarboxylate[36] with sodium allyl oxide in tetrahydrofuran at −5 °C. Stereochemical assignment of the cis and trans isomers is consonant with NMR, IR, and UV spectral data[39] (see Experimental Section).



1 **2**

All attempts to detect intramolecular cycloaddition from the thermally generated azomethine ylides derived from aziridines **1** and **2** failed. The only reaction found to occur upon thermolysis corresponded to cis–trans isomerization about the three-membered ring. The two azomethine ylides **3** and **4**, related by rotation about the C–N axis, are plausible intermediates in this isomerization. The stationary state produced favored the thermodynamically more stable cis isomer (ratio **1**/**2** = 7:3).[40]

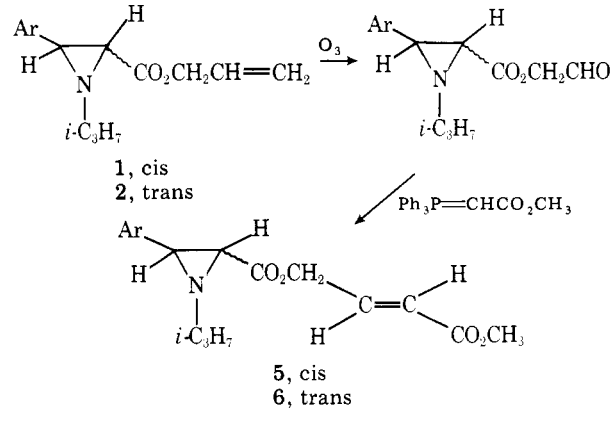


1 **2**

3 **4**

Our inability to isolate an internal 1,3-adduct with these systems is perfectly consistent with the principles of frontier MO theory.[41-44] According to the frontier orbital treatment of 1,3-dipolar cycloadditions, the relative reactivity of a given 1,3-dipole toward a series of dipolarophiles will be determined primarily by the extent of stabilization afforded the transition state of interaction of the frontier orbitals of the two reactants. When azomethine ylides are used as 1,3-dipoles, the dipole highest occupied (HOMO) and dipolarophile lowest unoccupied (LUMO) interaction will be of greatest importance in stabilizing the transition state. Azomethine ylides are known to react most rapidly with electron deficient alkenes, since such a pair of addends possesses a narrow dipole HOMO–dipolarophile LUMO gap.[42] Bimolecular reactions of azomethine ylides with terminal olefins have never been observed, thereby indicating that the dipole LUMO–dipolarophile HOMO interaction is never large. Thus, the absence of an internal cycloadduct from the thermolysis of aziridine **1** or **2** can be attributed to a large HOMO–LUMO gap which exists between the transient azomethine ylide and the olefinic double bond. The only reaction which occurs corresponds to cis–trans isomerization about the aziridine ring.

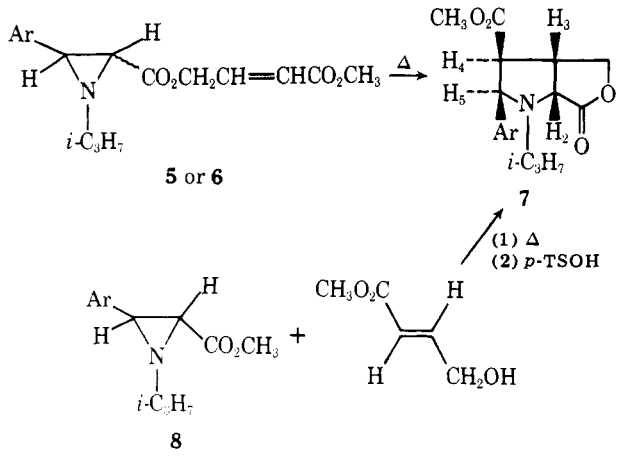
Placement of an electron-withdrawing substituent on the π bond should lower the dipolarophile LU energy and thereby accelerate the rate of 1,3-dipolar cycloaddition. Thus, it became of interest to study the intramolecular cycloaddition of an unsaturated aziridine carboxylate which possessed an electron-withdrawing substituent on the double bond in order to determine whether this electronic perturbation would favor intramolecular cycloaddition. To this end we synthesized (*E*)-*cis*- and -*trans*-3-carbomethoxy-2-propenyl 1-isopropyl-2-(*p*-biphenyl)-3-aziridinecarboxylates (**5** and **6**). These compounds were prepared by subjecting aziridines **1** and **2** to ozonolysis followed by treatment of the resulting aldehydes with carbomethoxymethyltriphenylphosphorane.



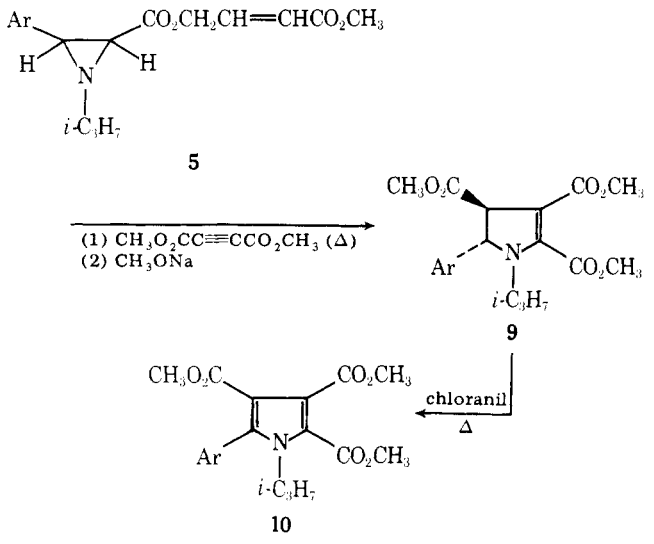
1, cis
2, trans

5, cis
6, trans

Heating either *cis*-aziridine **5** or *trans*-aziridine **6** in benzene led to the complete consumption of reactant in 24 h. The only product isolated in high yield was methyl (3aα,5α,6α,6aα)-hexahydro-4-(1-methylethyl)-3-oxo-5-biphenyl-2*H*-furo-[3,2-*b*]pyrrole-6-carboxylate (**7**): mp 154–155 °C; NMR (100 MHz) δ 1.00 and 1.20 (doublets, 6 H, J = 6.0 Hz), 3.30 (s, 3 H), 3.20–3.80 (m, 2 H), 4.10 (d, 1 H, J = 9.0 Hz), 4.30–4.48 (m, 2 H), 4.65 (d, 1 H, J = 8.0 Hz), and 7.05–7.65 (m, 9 H). The stereochemical assignment of structure **7** rests on the magnitude of the C_4–C_5 coupling constant ($J_{4,5}$ = 8.0 Hz) and its relationship to appropriate model systems.[36,45] Another useful criterion for assigning configurations in the pyrrolidine series is that the ester methyl signal appears at high field when it is adjacent to a cis aromatic ring.[46] An inspection of models reveals that only the methyl group of the C_4 substituent can be oriented in the shielding cone of the aromatic nucleus (δ 3.30), and this can occur only when the C_4 and C_5 substituents are cis. Assuming retention of dipolarophile stereochemistry, it follows that protons H_3 and H_4 in adduct **7** must be trans to each other. Finally, protons H_2 and H_3 can be fixed as being cis to each other by virtue of the observed cis coupling constant (J = 9.0 Hz). The corresponding trans coupling constant encountered with related systems has a value of less than 4.0 Hz.[36] The structure of the intramolecular cycloadduct **7** was further confirmed by an unequivocal synthesis. Thermolysis of *trans*-methyl 1-isopropyl-2-(*p*-biphenyl)-3-aziridinecarboxylate (**8**) with methyl γ-hydroxycrotonate followed by an acid-catalyzed lactonization produced the same cycloadduct as that obtained by heating aziridine **5** or **6**.

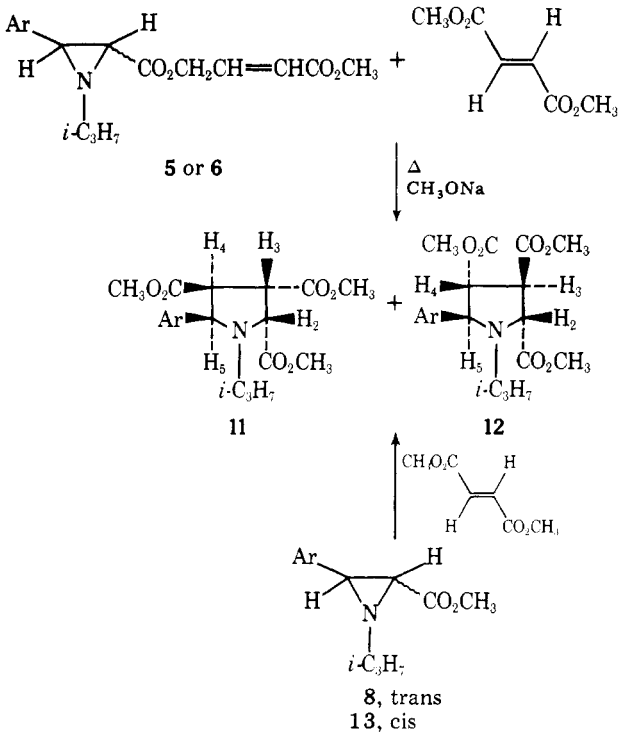


When the thermolysis of **5** was carried out in the presence of dimethyl acetylenedicarboxylate, the only product obtained after treatment with sodium methoxide was H_4,H_5-*trans*-trimethyl 1-isopropyl-5-(*p*-biphenyl)-Δ^2-pyrroline-2,3,4-tricarboxylate (**9**). Under these conditions, the formation of **7**, which is produced in high yield in the absence of a trapping agent, is entirely suppressed. The structure of **9** was confirmed by chloranil oxidation to trimethyl 1-isopropyl-5-(*p*-biphenyl)pyrrole-2,3,4-tricarboxylate (**10**). Pyrrole **10** was established by comparison with an authentic sample prepared according to the procedure of Woller and Cromwell.[36]



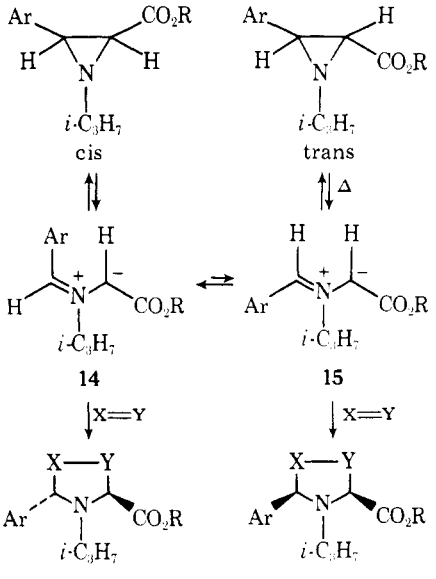
Thermolysis of aziridine **5** or **6** in the presence of dimethyl fumarate followed by treatment with sodium methoxide afforded a mixture of cycloadducts **11** and **12** (ratio 1:1). No detectable quantities of the intramolecular cycloadduct **7** could be detected in the crude reaction mixture. The same two cycloadducts were also formed by heating aziridine **8** or **13** with dimethyl fumarate.

The stereochemical assignments for adducts **11** and **12** were based on the same considerations used for assigning the stereochemistry of the intramolecular cycloadduct **7**. In line with the previous discussion, thermal cycloaddition of dimethyl fumarate with the azomethine ylide derived from **6** (or **8**) should result in protons H_3 and H_4 being trans to one another. The appearance of the C_4-carbomethoxy signal at relatively high field in adduct **11** (δ 3.10) is consistent with the vicinal shielding effect of the neighboring cis aromatic ring. Adduct **11** also exhibited the expected cis vicinal coupling constant (J = 7.0 Hz) expected for protons H_2 and H_3. On the other hand, adduct **12** exhibited signals for the methoxycarbonyl protons in the range δ 3.72–3.78, a coupling constant of 5.7 Hz for the H_4–H_5 protons, and a coupling constant of 1.0 Hz for the H_2–H_3 protons. The pertinent chemical shifts and coupling constants for these adducts are outlined in the Experimental Section.



All of the aforementioned reactions of aziridines **5**, **6**, **8**, and **13** with the activated alkenes conform to the concept of 1,3-dipolar cycloaddition reactions.[47] The thermal process of ring cleavage of aziridines involves stereospecific conrotatory ring opening.[37] Thus, the *cis*- and *trans*-aziridines used in this work would be expected to yield azomethine ylides **14** and **15**, respectively. These ylides can either equilibrate and ring close back to the aziridines[37] or, in the presence of an activated olefin, undergo stereospecific reaction to form the five-membered pyrrolidine ring. These cycloaddition reactions are known to be stereospecific and hence concerted.[47]

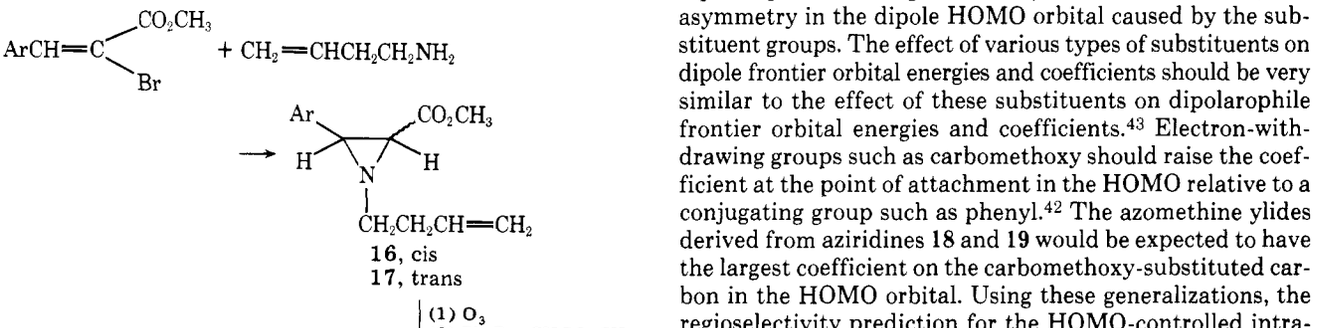
Our results show that cycloaddition of the azomethine ylides to dipolarophiles can compete with the equilibration process. Huisgen had previously shown that the more active the dipolarophile is, the higher will be the stereoselectivity of the overall process.[37] The fact that aziridines **1** and **2** undergo rapid cis–trans isomerization even though a neighboring π bond is present in the molecule can be attributed to the low



dipolarophilic activity of the terminal double bond. With this system, equilibration occurs at a much faster rate than internal dipolar addition. Attachment of an electron-withdrawing substituent to the double bond significantly enhances the internal cycloaddition rate, and consequently cis–trans isomerization about the aziridine ring does not occur. It is of interest to note that both the *cis*-aziridine **5** and the *trans*-aziridine **6** give rise to the same internal cycloadduct (i.e., **7**). Furthermore, the thermolysis of **5** and/or **6** in the presence of dimethyl fumarate produces the same two bimolecular cycloadducts **11** and **12**. Similar results were observed with *cis*- and *trans*-aziridines **8** and **13**. In all of the cases studied, the cycloadduct(s) obtained corresponds to exclusive cycloaddition of azomethine ylide **14** with the available dipolarophile. This can be accounted for by assuming that the *cis*-ylide **15** undergoes rotation to the thermodynamically more stable *trans*-ylide **14** at a faster rate than cycloaddition. Apparently, repulsive van der Waals forces of interaction of the carbomethoxy and biphenyl moieties with the *N*-isopropyl group are greater with the *cis*-ylide **15** than with the *trans*-ylide **14**, thus giving the latter an energetic advantage. Furthermore, the steric congestion which results from the carbomethoxy (or biphenyl)–*N*-isopropyl interaction in the 1,3-dipole generated from the *trans*-aziridine (i.e., **15**) would also account for the slower rate of cycloaddition of this ylide. Similar results have been reported in the literature with related systems, thereby providing strong support for these arguments.[36,48,49]

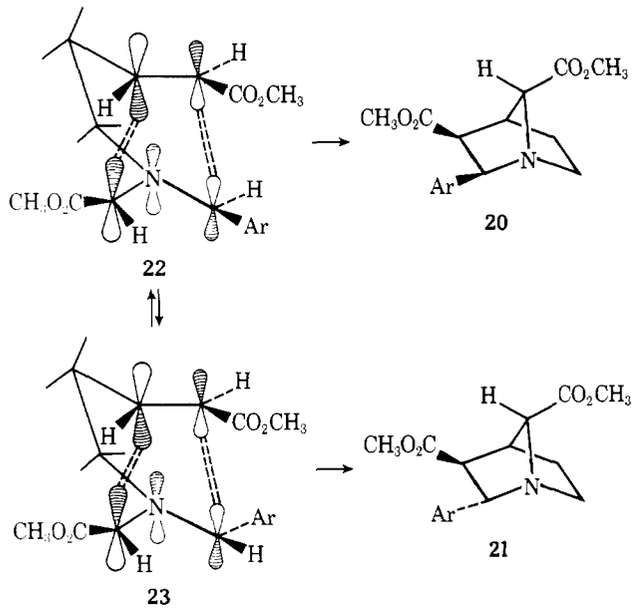
An additional system which was also studied involved the thermal chemistry of *cis*- (**18**) and *trans*-methyl *N*-(4-carbomethoxy-3-butenyl)-2-(*p*-biphenyl)-3-aziridinecarboxylate (**19**). Aziridine esters **16** and **17** were first synthesized by reaction of a 15-fold excess of 4-amino-1-butene with methyl α-bromo-*p*-phenylcinnamate. Stereochemical assignments were made on the basis of NMR spectroscopy. Aziridines **16** and **17** were found to equilibrate in refluxing benzene. All attempts to induce an intramolecular dipolar cycloaddition with these systems failed. The desired aziridine carboxylates **18** and **19** were readily prepared from **16** and **17** by ozonolysis of the terminal methylene group followed by treatment of the resulting aldehydes with carbomethoxymethyltriphenylphosphorane.

Heating either **18** or **19** in benzene afforded a mixture of two intramolecular cycloadducts **20** (37%) and **21** (30%). The NMR spectrum of the major adduct **20**, mp 173–174 °C, showed signals at δ 1.10–1.45 (m, 1 H), 1.65–2.10 (m, 1 H), 2.50–2.85 (m, 1 H), 2.95 (d, 1 H, J = 8.0 Hz), 3.10 (d, 1 H, J = 4.0 Hz), 3.26 (s, 3 H), 3.35–3.65 (m, 1 H), 3.80 (s, 3 H), 4.27 (d, 1 H, J = 8.0 Hz), 4.42 (s, 1 H), and 7.15–7.70 (m, 9 H). External irradiation of the multiplet at δ 1.65–2.10 caused the doublet at δ 3.10 to collapse to a singlet. Irradiation of the doublet at δ 2.95 collapsed the doublet at δ 4.27 to a singlet. The appearance of one of the carbomethoxy signals (C_3) at 0.54 ppm higher field than that of the other is compatible with the assigned stereochemistry. The observed doublet of the bridgehead hydrogen H_4 (J = 4.0 Hz) fixes the carbomethoxy group in the 3 position as being exo. If the carbomethoxy group at C_3 were in the endo position, proton H_4 would have appeared as a triplet. Finally, the large cis vicinal coupling constant for



C_2 H and C_3 H ($J_{2,3}$ = 8.0 Hz) is also in agreement with values reported in the literature for endo–endo coupling.[50] The stereochemical assignment for the minor cycloadduct **21** is based on the observation that this adduct exhibits signals for the two carbomethoxy groups at δ 3.65 and 3.68. The bridgehead proton H_4 appears as a doublet at δ 3.30 (J = 4.0 Hz), and the observed coupling of $J_{2,3}$ = 5.0 Hz is in good agreement with reported values for exo–endo coupling in bicyclo[2.2.1]heptanes.[50]

As was mentioned earlier, the dipole HOMO–dipolarophile LUMO orbitals control the rate and regioselectivity of 1,3-dipolar cycloadditions with azomethine ylides. The favored cycloadduct will be that formed by union of the atoms with the largest coefficient in the dipole HOMO and dipolarophile LUMO orbitals. An electron deficient olefin such as the carbomethoxy-substituted π system present in **18** and **19** has the largest coefficient on the 2-substituted carbon in the LUMO orbital. Although unsymmetrically substituted azomethine ylides can, in principle, form regioisomers with unsymmetrical dipolarophiles, the regiochemistry will be controlled by the asymmetry in the dipole HOMO orbital caused by the substituent groups. The effect of various types of substituents on dipole frontier orbital energies and coefficients should be very similar to the effect of these substituents on dipolarophile frontier orbital energies and coefficients.[43] Electron-withdrawing groups such as carbomethoxy should raise the coefficient at the point of attachment in the HOMO relative to a conjugating group such as phenyl.[42] The azomethine ylides derived from aziridines **18** and **19** would be expected to have the largest coefficient on the carbomethoxy-substituted carbon in the HOMO orbital. Using these generalizations, the regioselectivity prediction for the HOMO-controlled intramolecular cycloaddition of aziridines **18** and **19** proves to be correct. Thus, the formation of cycloadducts **20** and **21** from aziridines **18** and **19** is perfectly consistent with the principles of frontier MO theory. Conrotatory ring opening of aziridine **18** should give azomethine ylide **22**, while thermolysis of **19** would be expected to give **23**. It should be noted that isomerization of the azomethine ylides (**22** $\rightleftarrows$ **23**) is competitive with the intramolecular cycloaddition reaction. Apparently the carbomethoxy-substituted olefin is not reactive enough to suppress the isomerization process.



In conclusion, our results show that the intramolecular dipolar cycloaddition reaction of unsaturated aziridines is a general, synthetically useful, and mechanistically intruiging process. It is evident from our data that the intramolecular cycloaddition reaction will only occur when an electron-withdrawing substituent is attached to the double bond. We are continuing to examine the effects of geometry and substituents on the reaction and will report additional findings at a later date.

Experimental Section

All melting points and boiling points are uncorrected. Elemental analyses were performed by Atlantic Microlabs, Atlanta, Ga. The infrared absorption spectra were determined on a Perkin-Elmer Model 137 Infracord spectrometer. The ultraviolet absorption spectra were measured with a Cary Model 14 recording spectrophotometer using 1-cm matched cells. The proton magnetic resonance spectra were determined at 100 MHz using a Jeolco-MH-100 and a Varian XL-100 spectrometer. Mass spectra were determined with a Perkin-Elmer RMU6 mass spectrometer at an ionizing voltage of 70 eV.

Preparation of (*E*)-*trans*-3-Carbomethoxy-2-propenyl 1-Isopropyl-2-(*p*-biphenyl)-3-aziridinecarboxylate (6). To a solution containing 885 mg of *trans*-methyl 1-isopropyl-2-(*p*-biphenyl)-3-aziridinecarboxylate (**8**)[36] in 10 mL of tetrahydrofuran at −5 °C was slowly added a solution of sodium allyl oxide prepared by dissolving 138 mg of sodium in 60 mL of allyl alcohol. After the addition was complete, the mixture was allowed to stir for 15 min at −5 °C. The mixture was diluted with 30 mL of water and extracted with ether. Removal of the solvent under reduced pressure left a pale yellow oil which was recrystallized from pentane to give 700 mg (70%) of *trans*-allyl 1-isopropyl-2-(*p*-biphenyl)-3-aziridinecarboxylate (**2**) as a white solid: mp 39–40 °C; IR (KBr) 5.78, 7.23, 8.53, 9.89, 11.98, 12.03, 13.32, and 14.33 μm; NMR ($CDCl_3$, 100 MHz) δ 1.04 (d, 3 H, J = 6.0 Hz), 1.20 (d, 3 H, J = 6.0 Hz), 2.74 (d, 1 H, J = 2.5 Hz), 2.80–3.30 (m, 2 H), 4.62 (d, 2 H, J = 6.0 Hz), 5.14–5.40 (m, 2 H), 5.70–6.15 (m, 1 H), and 7.00–7.65 (m, 9 H); UV (methanol) 256 nm (ε 26 000); *m/e* 321 (M^+), 283, 240, 234, 209, 184 (base), 183, 169, and 154.

Anal. Calcd for $C_{21}H_{23}NO_2$: C, 78.47; H, 7.21; N, 4.36. Found: C, 78.51; H, 7.17; N, 4.20.

A 642-mg sample of the above aziridine in 150 mL of methanol was subjected to ozonolysis at −78 °C. The reaction mixture was allowed to warm to −20 °C, and 10 mL of dimethyl sulfide was added. After standing for 4 h at 0 °C, the solution was concentrated under reduced pressure. The resulting yellow oil was taken up in ether, washed with water, and dried over magnesium sulfate, and the solvent was removed under reduced pressure. The resulting aldehyde was immediately used in the next step.

A solution containing 600 mg of the above oil and 668 mg of carbomethoxymethyltriphenylphosphorane[51] in 100 mL of benzene was stirred at 25 °C for 24 h. Removal of the solvent under reduced pressure left a yellow oil which was subjected to Florisil column chromatography using a 1:1 ether–pentane mixture as the eluent. The major fraction isolated contained 520 mg (69%) of a clear oil whose structure is assigned as (*E*)-*trans*-3-carbomethoxy-2-propenyl 1-isopropyl-2-(*p*-biphenyl)-3-aziridinecarboxylate (**6**) on the basis of the following data: IR (neart) 3.42, 5.85, 6.02, 6.43, 6.77, 7.00, 7.89, 8.60, 9.93, 11.98, 13.04, 13.34, and 14.40 μm; NMR ($CDCl_3$, 100 MHz) δ 1.05 (d, 3 H, J = 6.0 Hz), 1.18 (d, 3 H, J = 6.0 Hz), 2.78 (d, 1 H, J = 2.0 Hz), 2.83–3.35 (m, 2 H), 3.70 (s, 3 H), 4.80 (dd, 1 H, J = 4.5 and 2.0 Hz), 6.04 (dt, 1 H, J = 16.0 and 2.0 Hz), 6.92 (dt, 1 H, J = 16.0 and 4.5 Hz), and 7.20–7.60 (m, 9 H); UV (methanol) 258 nm (ε 25 800); *m/e* 379 (M^+), 334, 320, 309, 296, 253, 239, 220, 209, 183 (base), 153, 107, and 73.

Anal. Calcd for $C_{23}H_{25}NO_4$: C, 72.80; H, 6.64; N, 3.69. Found: C, 72.86; H, 6.75; N, 3.52.

Preparation of (*E*)-*cis*-3-Carbomethoxy-2-propenyl 1-Isopropyl-2-(*p*-biphenyl)-3-aziridinecarboxylate (5). To a solution containing 885 mg of *cis*-methyl 1-isopropyl-2-(*p*-biphenyl)-3-aziridinecarboxylate (**13**)[36] in 10 mL of tetrahydrofuran at −5 °C was slowly added a solution of sodium allyl oxide prepared by dissolving 138 mg of sodium in 6.0 mL of allyl alcohol. After the addition was completed, the mixture was diluted with 300 mL of water and extracted with ether. The ethereal layer was dried over magnesium sulfate, and the solvent was removed under reduced pressure to give 850 mg (88%) of *cis*-allyl 1-isopropyl-2-(*p*-biphenyl)-3-aziridinecarboxylate (**1**) as a clear oil: IR (neat) 3.38, 5.71, 5.79, 6.72, 7.23, 7.48, 8.52, 9.62, 9.89, 10.72, 11.74, 13.20, and 14.31 μm; NMR ($CDCl_3$, 100 MHz) δ 1.15 (d, 6 H, J = 6.0 Hz), 1.50–1.90 (m, 1 H), 2.45 (d, 1 H, J = 7.0 Hz), 2.85 (d, 1 H, J = 7.0 Hz), 4.35 (broad d, 2 H, J = 6.0 Hz), 4.85–5.10 (m, 2 H), 5.30–5.75 (m, 1 H), and 7.10–7.65 (m, 9 H).

A 900-mg sample of the above aziridine in 200 mL of methanol was subjected to ozonization at −78 °C. The reaction mixture was allowed to warm to −20 °C, and 10 mL of dimethyl sulfide was added. After standing for 4 h at 0 °C, the solution was concentrated under reduced pressure. The crude residue was taken up in ether, washed with water, dried over magnesium sulfate, and concentrated under reduced pressure. The resulting aldehyde was immediately used in the next step.

A solution containing the above aldehyde and 1.0 g of carbomethoxymethyltriphenylphosphorane[51] in 100 mL of benzene was stirred at 25 °C for 24 h. The solvent was removed under reduced pressure, and the resulting residue was chromatographed on a Florisil column using a 1:1 ether–pentane mixture as the eluent. The major fraction obtained contained 750 mg of a clear oil whose structure was assigned as (*E*)-*cis*-3-carbomethoxy-2-propenyl 1-isopropyl-2-(*p*-biphenyl)-3-aziridinecarboxylate (**5**) on the basis of the following data: IR (neat) 3.36, 5.67, 5.76, 6.70, 6.95, 7.77, 8.55, 9.60, 11.70, 13.15, and 14.35 μm; NMR ($CDCl_3$, 100 MHz) δ 1.15 (d, 6 H, J = 6.0 Hz), 1.30–1.80 (m, 1 H), 2.48 (d, 1 H, J = 6.0 Hz), 2.86 (d, 1 H, J = 6.0 Hz), 3.40 (s, 3 H), 4.42 (d, 2 H, J = 4.0 Hz), 5.52 (dt, 1 H, J = 16.0 and 2.0 Hz), 6.50 (dt, 1 H, J = 16.0 and 4.0 Hz), and 7.00–7.55 (m, 9 H); UV (methanol) 256 nm (ε 19 100); *m/e* 379 (M^+), 334, 320, 251, 222, 206, 183 (base), 155, 128, 106, and 78.

Anal. Calcd for $C_{23}H_{25}NO_4$: C, 72.80; H, 6.64; N, 3.69. Found: C, 72.86; H, 6.74; N, 3.69.

Thermolysis of (*E*)-*cis*- (5) or -*trans*-Carbomethoxy-2-propenyl 1-Isopropyl-2-(*p*-biphenyl-3-aziridinecarboxylate (6). A 383-mg sample of aziridine **5** (or **6**) in 20 mL of benzene was heated at reflux for 24 h. Removal of the solvent under reduced pressure left a yellow solid which was recrystallized from ether–pentane to give 275 mg (73%) of a white solid, mp 154–155 °C, whose structure was assigned as methyl (3aα,5α,6α,6aα)-hexahydro-4-(1-methylethyl)-3-oxo-5-biphenyl-2*H*-furo[3,2-*b*]pyrrole-6-carboxylate (**7**) on the basis of its spectral properties: IR (KBr) 2.95, 3.42, 5.64, 5.82, 6.80, 7.02, 7.30, 7.62, 7.81, 8.33, 8.52, 9.42, 9.87, 10.20, 11.54, 11.92, 13.02, 13.38, and 14.33 μm; NMR ($CDCl_3$, 100 MHz) δ 1.00 and 1.20 (doublets, 6 H, J = 6.0 Hz), 3.30 (s, 3 H), 3.20–3.80 (m, 2 H), 4.10 (d, 1 H, J = 9.0 Hz), 4.30–4.48 (m, 2 H), 4.65 (d, 1 H, J = 8.0 Hz), and 7.05–7.65 (m, 9 H); UV (methanol) 255 nm (ε 21 000); *m/e* 379 (M^+), 364, 337, 321 (base), 279, 264, 248, 221, 193, 180, 167, 152, and 93.

Anal. Calcd for $C_{23}H_{25}NO_4$: C, 72.80; H, 6.64; N, 3.69. Found: C, 72.68; H, 6.74; N, 3.69.

The structure of the cycloadduct was further verified by comparison with an independently synthesized sample. A solution containing 295 mg of *trans*-methyl 1-isopropyl-2-(*p*-biphenyl)-3-aziridinecarboxylate (**8**) and 116 mg of methyl γ-hydroxycrotonate[52] in 20 mL of benzene was heated at reflux for 3 days. The mixture was cooled to room temperature, and 2 mg of *p*-toluenesulfonic acid was added. The solution was heated at reflux for an additional 24 h, cooled, washed with water, dried over magnesium sulfate, and concentrated under reduced pressure. The resulting residue was crystallized from ether to give 27 mg, mp 154–155 °C, whose spectral properties were identical with the cycloadduct **7** obtained from the thermolysis of aziridine **5**.

The same cycloadduct was obtained in 81% yield from the thermolysis of the isomer *trans*-aziridine **6**.

Thermolysis of (*E*)-*cis*-3-Carbomethoxy-2-propenyl 1-Isopropyl-2(*p*-biphenyl)-3-aziridinecarboxylate in the Presence of Dimethyl Acetylenedicarboxylate. A solution containing 190 mg of aziridine **5** and 142 mg of dimethyl acetylenedicarboxylate in 20 mL of benzene was heated at reflux for 24 h. Removal of the solvent under reduced pressure left a yellow oil whose NMR spectrum indicated the complete absence of cycloadduct **7**. The crude oil was taken up in 10 mL of benzene, and 1 mL of a 1 N sodium methoxide solution was added. The mixture was vigorously stirred at 25 °C for 24 h. The benzene layer was separated, washed with water, and dried over magnesium sulfate. Removal of the solvent left a yellow oil which was purified by chromatography over a Florisil column using a 2% ethyl acetate–benzene mixture as the eluent. The major component contained 110 mg (52%) of a clear oil whose structure was assigned as H_4,H_5-*trans*-trimethyl 1-isopropyl-5-(*p*-biphenyl-Δ^2-pyrroline-2,3,4-tricarboxylate (**9**) by comparison with an authentic sample:[36] NMR ($CDCl_3$ 100 MHz) δ 0.93 and 1.24 (two doublets, 6 H, J = 6.5 Hz), 3.33–3.80 and 3.63 (m and s, 4 H, isopropylmethine and methoxy group), 3.73 (d, 1 H, J = 6.0 Hz), 3.76 and 3.96 (two s, 3 H), 4.93 (d, 1 H, J = 6.0 Hz), and 7.3–7.8 (m, 9 H).

A solution containing 50 mg of the above cycloadduct and 60 mg of chloranil in 10 mL of xylene was heated at reflux for 6 h. The solution was diluted with ether and washed with a 4% sodium hydroxide solution containing 1% of sodium bisulfite and then with water. The solution was dried over magnesium sulfate and concentrated under reduced pressure to give 38 mg (72%) of trimethyl 1-isopropyl-5-(*p*-biphenyl)pyrrole-2,3,4-tricarboxylate (**10**): mp 172–173 °C; NMR ($CDCl_3$, 100 MHz) δ 1.45 (d, 6 H, J = 7.6 Hz), 3.58 (s, 3 H), 3.86 (s, 3 H), 3.94 (s, 3 H), 4.60–4.80 (m, 1 H), and 7.3–7.80 (m, 9 H). The structure of **10** was verified by comparison with an authentic sample prepared according to the procedure of Woller and Cromwell.[36]

Thermolysis of (*E*)-*trans*-3-Carbomethoxy-2-propenyl 1-Isopropyl-2-(*p*-biphenyl)-3-aziridinecarboxylate in the Presence of Dimethyl Fumarate. A solution containing 190 mg of aziridine **6** and 72 mg of dimethyl fumarate in 20 mL of benzene was heated at reflux for 24 h. Removal of the solvent left a yellow oil whose NMR spectrum indicated the complete absence of cycloadduct **7**. The above oil was taken up in 10 mL of methanol to which was added 1 mL of a 1 N sodium methoxide solution. The mixture was allowed to stir at 25 °C for 24 h. Removal of the solvent left a yellow oil which was taken up in ether. The ethereal solution was washed with water and dried over magnesium sulfate. Removal of the solvent left an oil which was recrystallized from ether to give 80 mg (37%) of H_2,H_3-*cis*-H_3,H_4-*trans*-H_4,H_5-*cis*-trimethyl 1-isopropyl-5-(*p*-biphenyl)pyrrolidine-2,3,4-tricarboxylate (**11**) as a white solid: mp 109–110 °C; IR (KBr) 5.74, 6.96, 7.22, 7.47, 8.32, 8.50, 9.90, 13.19, and 14.30 μm; NMR ($CDCl_3$, 100 MHz) δ 0.90 and 1.00 (two doublets, 6 H, J = 7.0 Hz), 2.75–3.15 (m, 1 H), 3.10 (s, 3 H), 3.65 (s, 3 H), 3.70 (s, 3 H), 3.96 (dd, 1 H, J = 10.0 and 7.0 Hz), 4.16 (t, 1 H, J = 10.0 Hz), 4.47 (d, 1 H, J = 7.0 Hz), 4.84 (d, 1 H, J = 10.0 Hz), and 7.2–7.7 (m, 9 H); UV (methanol) 255 nm (ϵ 22 600); *m/e* 438 (M^+), 424, 395, 379 (base), 348, 320, 311, 267, 192, 181, 179, 166, 130, 106, 92, and 78.

Anal. Calcd for $C_{25}H_{29}NO_6$: C, 68.32; H, 6.65; N, 3.19. Found: C, 68.12; H, 6.72; N, 3.05.

Evaporation of the mother liquors left a clear oil which was crystallized from pentane to give 75 mg (35%) of H_2,H_3-*trans*-H_3,H_4-*trans*-H_4,H_5-*trans*-trimethyl 1-isopropyl-5-(*p*-biphenyl)pyrrolidine-2,3,4-tricarboxylate (**12**) as a white solid: mp 124–125 °C; IR (KBr) 3.41, 5.81, 6.76, 7.02, 7.27, 8.05, 8.35, 9.83, 13.12, 13.65, and 14.45 μm; NMR ($CDCl_3$, 100 MHz) δ 0.85 and 1.05 (two doublets, 6 H, J = 6.0 Hz), 2.76–3.05 (m, 1 H), 3.50–3.70 (m, 2 H), 3.72 (s, 6 H), 3.78 (s, 3 H), 4.45 (broad s, 1 H), 4.78 (broad d, 1 H, J = 5.7 Hz), and 7.20–7.70 (m, 9 H); UV (methanol) 255 nm (ϵ 22 300); *m/e* 438 (M^+), 424, 400, 385, 384 (base), 349, 321, 289, 278, 247, 221, 220, 192, 181, and 166.

Anal. Calcd for $C_{25}H_{29}NO_6$: C, 68.32; H, 6.65; N, 3.19. Found: C, 68.28; H, 6.76; N, 3.06.

The structures of cycloadducts **11** and **12** were further verified by comparison with independently synthesized samples prepared from the thermolysis of *trans*-methyl 1-isopropyl-2-(*p*-biphenyl)-3-aziridinecarboxylate (**8**) with dimethyl fumarate. A solution containing 150 mg of **8** and 72 mg of dimethyl fumarate in 20 mL of benzene was heated at reflux for 24 h. Removal of the solvent left a colorless oil which was fractionally crystallized to give samples of cycloadducts **11**, mp 110–112 °C, and **12**, mp 124–125 °C. These compounds were identical in every detail with those prepared from the thermolysis of **5** with dimethyl fumarate. The same two cycloadducts were obtained from the thermolysis of *cis*-aziridine **6** or **13** in the presence of dimethyl fumarate.

Preparation of *cis*- and *trans*-Methyl *N*-(4-Carbomethoxy-3-butenyl)-2-(*p*-biphenyl)-3-aziridinecarboxylate. A solution containing 2.0 g of *trans*-methyl α-bromo-*p*-phenylcinnamate[36] and 9.0 g of 4-amino-1-butene[53] in 20 mL of benzene was stirred for 4 days at room temperature. At the end of this time the mixture was diluted with ether and the precipitated amine salt was collected. The solution was concentrated under reduced pressure, and the resulting residue was subjected to Florisil column chromatography using a 1:1 ether–pentane mixture as the eluent. The major fraction contained a mixture of *cis*- (**16**) and *trans*-methyl 1-(3-butenyl)-2-(*p*-biphenyl)-3-aziridinecarboxylate (**17**). All attempts to induce an intramolecular dipolar cycloaddition of these compounds failed.

A solution containing 1.0 g of the above mixture in 200 mL of methanol was cooled to −78 °C and saturated with an ozone stream. The reaction was allowed to warm to −20 °C, and 10 mL of dimethyl sulfide was added. After standing at 0 °C for 4 h, the solvent was removed under reduced pressure to give 800 mg of a yellow oil which was immediately used in the next step.

A solution containing the above oil and 1.0 g of carbomethoxymethyltriphenylphosphorane[51] in 100 mL of benzene was stirred at room temperature for 24 h. Removal of the solvent under reduced pressure left a yellow residue which was subjected to Florisil column chromatography using a 40% ether–pentane mixture as the eluent. The first component isolated from the column contained 190 mg (16%) of *trans*-methyl *N*-(4-carbomethoxy-3-butenyl)-3-(*p*-biphenyl)-3-aziridinecarboxylate (**19**), as a crystalline solid: mp 89–90 °C; IR (KBr) 5.83, 6.08, 7.00, 7.29, 7.85, 8.39, 8.51, 9.30, 11.44, and 13.29 μm; NMR ($CDCl_3$, 100 MHz) δ 2.30–2.65 (m, 2 H), 2.75 (d, 1 H, J = 2.0 Hz), 2.85–3.45 (m, 3 H), 3.65 (s, 3 H), 3.75 (s, 3 H), 5.85 (broad d, 1 H, J = 16.0 Hz), 6.80–7.25 (m, 1 H), and 7.25–7.75 (m, 9 H); UV (methanol) 256 nm (ϵ 26 600); *m/e* 365 (M^+), 272, 271 (base), 243, 242, 195, 185, 166, and 110.

Anal. Calcd for $C_{22}H_{23}NO_4$: C, 72.31; H, 6.34; N, 3.83. Found: C, 72.54; H, 6.55; N, 4.19.

The second component isolated from the chromatography column contained 380 mg (32%) of a crystalline solid, mp 113–114 °C, whose structure was assigned as *cis*-methyl *N*-(4-carbomethoxy-3-butenyl)-2-(*p*-biphenyl)-3-aziridinecarboxylate (**18**) on the basis of the following data: IR (KBr) 5.74, 5.79, 6.02, 6.95, 7.24, 7.97, 8.21, 8.32, 8.47, 8.59, 8.92, 9.96, 11.75, 13.11, and 14.25 μm; NMR ($CDCl_3$, 100 MHz) δ 2.30–2.80 (m, 4 H), 2.80–3.10 (m, 2 H), 3.50 (s, 3 H), 3.70 (s, 3 H), 5.85 (d, 1 H, J = 16.0 Hz), 6.80–7.20 (m, 1 H), and 7.20–7.70 (m, 9 H); UV (methanol) 256 nm (ϵ 24 000); *m/e* 365 (M^+), 272, 271 (base), 249, 239, 220, 208, 179, 166, 153, 143, 101, and 95.

Anal. Calcd for $C_{22}H_{23}NO_4$: C, 72.31; H, 6.34; N, 3.83. Found: C, 72.20; H, 6.48; N, 3.78.

Thermolysis of Methyl *N*-(4-Carbomethoxy-3-butenyl)-2-(*p*-biphenyl)-3-aziridinecarboxylate. A 200-mg sample of either *cis*-aziridine **18** or *trans*-aziridine **19** in 40 mL of benzene was heated at reflux for 36 h. Removal of the solvent left an oily solid which was recrystallized from ether to give 74 mg (37%) of a white solid, mp 173–174 °C, whose structure was assigned as dimethyl (2-*exo*-3-*exo*-7-*anti*)-2-biphenyl-1-azabicyclo[2.2.1]heptane-3,7-dicarboxylate (**20**) on the basis of the following data: IR (KBr) 5.76, 5.82, 7.02, 7.27, 8.30, 8.63, 8.71, 9.18, 9.44, 11.46, 11.76, 13.16, and 14.33 μm; UV (methanol) 255 nm (ϵ 3920); *m/e* 365 (M^+, base), 341, 308, 307, 289, 275, 263, 253, 220, 195, 168, and 166; NMR ($CDCl_3$, 100 MHz) δ 1.10–1.45 (m, 1 H), 1.65–2.10 (m, 1 H), 2.50–2.85 (m, 1 H), 2.95 (d, 1 H, J = 8.0 Hz), 3.10 (d, 1 H, J = 4.0 Hz), 3.26 (s, 3 H), 3.35–3.65 (m, 1 H), 3.80 (s, 3 H), 4.27 (d, 1 H, J = 8.0 Hz), 4.42 (s, 1 H), and 7.15–7.70 (m, 9 H). External irradiation of the multiplet at δ 1.65–2.10 caused the doublet at δ 3.10 to collapse to a singlet. Irradiation of the doublet at δ 2.95 collapsed the doublet at δ 4.27 to a singlet.

Anal. Calcd for $C_{22}H_{23}NO_4$: C, 72.31 H, 6.34; N, 3.83. Found: C, 72.50; H, 6.36; N, 3.70.

Evaporation of the mother liquors left a yellow oil which was subjected to thick-layer chromatography using a 10% chloroform–ether mixture as the eluent. The major band contained 60 mg (30%) of a clear oil whose structure was assigned as dimethyl (2-*endo*,3-*exo*,7-*anti*)-2-biphenyl-1-azabicyclo[2.2.1]heptane-3,7-dicarboxylate (**21**) on the basis of the following data: IR (neat) 3.42, 5.75, 5.80, 6.74, 7.01, 8.33, 8.97, 9.52, 13.09, 13.88, and 14.36 μm; UV (methanol) 255 nm (ϵ 3680); *m/e* 365 (M^+), 364, 363, 350, 339, 309, 277, 229, 208, 183, 142, 107, and 73; NMR ($CDCl_3$, 100 MHz) δ 0.96–1.32 (m, 1 H), 1.50–1.90 (m, 1 H), 2.50 (d, 1 H, J = 5.0 Hz), 2.60–2.80 (m, 2 H), 3.30 (d, 1 H, J = 4.0 Hz), 3.50 (s, 1 H), 3.65 (s, 3 H), 3.68 (s, 3 H), 5.02 (d, 1 H, J = 5.0 Hz), and 7.24–7.82 (m, 9 H). Irradiation of the multiplet at δ 1.50–1.90 caused the collapse of the doublet at δ 3.30 to a singlet. Irradiation of the doublet at δ 5.02 caused the doublet at δ 2.50 to collapse to a singlet.

Anal. Calcd for $C_{22}H_{23}NO_4$: C, 72.31; H, 6.34; N, 3.83. Found: C, 72.50; H, 6.36; N, 3.70.

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Registry No.—1, 68151-69-9; 2, 68151-70-2; 5, 68151-71-3; 6, 68199-22-4; 7, 68151-72-4; 8, 23214-22-4; 9, 23214-38-2; 10, 68151-73-5; 11, 68151-74-6; 12, 68199-23-5; 13, 23214-21-3; 16, 68151-75-7; 17, 68151-76-8; 18, 68151-77-9; 19, 68199-24-6; 20, 68151-78-0; 21, 68199-25-7; dimethyl acetylenedicarboxylate, 762-42-5; (*E*)-methyl γ-hydroxycrotonate, 29576-13-4; dimethyl fumarate, 624-49-7; *trans*-methyl α-bromo-*p*-phenylcinnamate, 23214-41-7; 4-amino-1-butene, 2524-49-4; carbomethoxymethyltriphenylphosphorane, 2605-67-6; sodium allyl oxide, 20907-32-8.

References and Notes

(1) For a recent review on intramolecular 1,3-dipolar cycloadditions, see A. Padwa, *Angew. Chem., Int. Ed. Engl.*, **15**, 123 (1976).
(2) W. Oppolzer, *Angew. Chem., Int. Ed. Engl.*, **16**, 10 (1977).
(3) D. S. C. Black, R. F. Crozier, and V. C. Davis, *Synthesis*, 205 (1975).
(4) N. A. LeBel and J. J. Whang, *J. Am. Chem. Soc.*, **81**, 6334 (1959).
(5) N. A. LeBel, *Trans. N. Y. Acad. Sci.*, **27**, 858 (1965).
(6) N. A. LeBel, M. E. Post, and J. J. Whang, *J. Am. Chem. Soc.*, **86**, 3759 (1964).
(7) N. A. LeBel and T. A. Lajiness, *Tetrahedron Lett.*, 2173 (1966).
(8) N. A. LeBel, G. H. J. Slusarczuk, and L. A. Spurlock, *J. Am. Chem. Soc.*, **84**, 4360 (1962).
(9) N. A. LeBel, N. D. Ojha, J. R. Menke, and R. J. Newland, *J. Org. Chem.*, **37**, 2806 (1972).
(10) N. A. LeBel and E. G. Banucci, *J. Org. Chem.*, **36**, 2440 (1971).
(11) W. Kirmse and H. Dietrich, *Chem. Ber.*, **100**, 2710 (1967).
(12) M. Schwarz, A. Besold, and E. R. Nelson, *J. Org. Chem.*, **30**, 2425 (1965).
(13) E. Piers, R. W. Britton, R. J. Keziere, and R. S. Smillie, *Can. J. Chem.*, **49**, 2623 (1971).
(14) B. M. Trost, R. M. Cory, P. H. Scudder, and H. B. Neubold, *J. Am. Chem. Soc.*, **95**, 7813 (1973).
(15) J. L. Brewbaker and H. Hart, *J. Am. Chem. Soc.*, **91**, 711 (1969).
(16) F. C. Uhle, *J. Org. Chem.*, **32**, 1596 (1967).
(17) P. A. Smith, J. M. Clegg, and J. H. Hall, *J. Org. Chem.*, **23**, 524 (1958).
(18) A. L. Logothetis, *J. Am. Chem. Soc.*, **87**, 749 (1965).
(19) R. Fusco, L. Garanti, and G. Zecchi, *J. Org. Chem.*, **40**, 1906 (1975).
(20) J. H. Hall, F. E. Behr, and R. L. Reed, *J. Am. Chem. Soc.*, **94**, 4952 (1972).
(21) W. Oppolzer, *Tetrahedron Lett.*, 3091 (1970).
(22) W. Oppolzer, *Tetrahedron Lett.*, 1707 (1972).
(23) R. Crigee, A. Banciu, and H. Keul, *Chem. Ber.*, **108**, 1642 (1975).
(24) R. Fusco, L. Garanti, and G. Zecchi, *Tetrahedron Lett.*, 269 (1974).
(25) L. Garanti, A. Vigevani, and G. Zecchi, *Tetrahedron Lett.*, 1527 (1976).
(26) A. Padwa and P. H. J. Carlsen, *J. Am. Chem. Soc.*, **98**, 2006 (1976); **99**, 1514 (1977); **97**, 3862 (1975); A. Padwa and N. Kamigata, *ibid.*, **99**, 1871 (1977); A. Padwa, A. Ku, A. Mazzu, and S. I. Wetmore, *ibid.*, **98**, 1048 (1976); A. Padwa and A. Ku, *ibid.*, **100**, 2181 (1978).
(27) H. Meier, H. Heimgartner, and H. Schmid, *Helv. Chim. Acta*, **60**, 1087 (1977).
(28) H. W. Heine and R. E. Peavy, *Tetrahedron Lett.*, 3123 (1965); H. W. Heine, R. Peavy, and A. J. Durbetaki, *J. Org. Chem.*, **31**, 3924 (1966).
(29) A. Padwa and L. Hamilton, *Tetrahedron Lett.*, 4363 (1965); *J. Heterocycl. Chem.*, **4**, 118 (1967).
(30) R. Huisgen, W. Scheer, G. Szeimies, and H. Huber, *Tetrahedron Lett.*, 397 (1966).
(31) A. Padwa and E. Glazer, *J. Org. Chem.*, **38**, 284 (1973); A. Padwa and L. Gehrlein, *J. Am. Chem. Soc.*, **94**, 4933 (1972).
(32) H. W. Heine, A. B. Smith, and J. D. Bower, *J. Org. Chem.*, **33**, 1097 (1968); H. W. Heine and R. Henzel, *ibid.*, **34**, 171 (1969).
(33) R. Huisgen, W. Scheer, and H. Mader, *Angew. Chem., Int. Ed. Engl.*, **8**, 602 (1969); **2**, 633, 644 (1963); R. Sustmann, R. Huisgen, and H. Huber, *Chem. Ber.*, **100**, 182 (1967); J. H. Hall and R. Huisgen, *Chem. Commun.*, 1187, 1188 (1971).
(34) J. W. Lown, G. Dallas, and T. W. Maloney, *Can. J. Chem.*, **47**, 3557, 4335 (1969); *Chem. Commun.*, 1543 (1968); 247 (1971); *Rec. Chem. Prog.*, **32**, 51 (1971).
(35) P. B. Woller and N. H. Cromwell, *J. Heterocycl. Chem.*, **5**, 579 (1968).
(36) P. B. Woller and N. H. Cromwell, *J. Org. Chem.*, **35**, 888 (1970).
(37) R. Huisgen, W. Scheer, and H. Huber, *J. Am. Chem. Soc.*, **89**, 1753 (1967).
(38) C. L. Deyrup, J. A. Deyrup, and M. Hamilton, *Tetrahedron Lett.*, 3437 (1977).
(39) A. E. Pohland, R. D. Badger, and N. H. Cromwell, *Tetrahedron Lett.*, 4369 (1965).
(40) R. E. Lutz and A. B. Turner, *J. Org. Chem.*, **33**, 516 (1968).
(41) I. Fleming, "Frontier Orbitals and Organic Chemical Reactions", Wiley, New York, 1976.
(42) K. N. Houk, J. Sims, C. R. Watts, and L. J. Luskus, *J. Am. Chem. Soc.*, **95**, 7301 (1973).
(43) K. N. Houk, J. Sims, R. E. Duke, Jr., R. W. Strozier, and J. K. George, *J. Am. Chem. Soc.*, **95**, 7287 (1973).
(44) R. Sustmann, *Tetrahedron Lett.*, 2717 (1971).
(45) A. Padwa and W. Eisenhardt, *Chem. Commun.*, 380 (1968).
(46) R. Huisgen, W. Scheer, G. Szeimies, and H. Huber, *Tetrahedron Lett.*, 397 (1966); J. H. Hall and R. Huisgen, *Chem. Commun.*, 1187, 1188 (1971).
(47) R. Huisgen, *J. Org. Chem.*, **33**, 2291 (1968); **41**, 403 (1976).
(48) R. Huisgen and H. Mader, *J. Am. Chem. Soc.*, **93**, 1777 (1971); H. Hermann, R. Huisgen, and H. Mader, *ibid.*, **93**, 1779 (1971).
(49) A. Padwa and L. Gehrlein, *J. Am. Chem. Soc.*, **94**, 4933 (1972).
(50) L. M. Jackman and S. Sternhell, "Applications of NMR Spectroscopy in Organic Chemistry", Pergamon Press, London, 1969, p 289.
(51) O. Isler, H. Gutmann, M. Montavan, R. Ruegg, G. Ryser, and P. Zeller, *Helv. Chim. Acta*, **40**, 1242 (1957).
(52) R. Rambaud, *Bull. Soc. Chim. Fr.*, **1**, 1317 (1934).
(53) E. Renk and J. D. Roberts, *J. Am. Chem. Soc.*, **83**, 878 (1961).