B. Ganem, and Dr. C. Wilcox, Jr., for many helpful discussions. We are grateful to the Research Foundation of the City University of New York for financial support of this work (CUNY FRAP Awards 01769 N and 10190).

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(3) (a) The synthesis of **1** is described in ref 1. Compound **3** was obtained from 1,4-butanedithiol and dibromomethane in presence of base.[4a] Bis(vinylmercapto)methane (**4**) has been synthesized from the reaction of vinyllithium and sulfur in tetrahydrofuran, followed by alkylation of the lithium vinyl thiolate[4b] with dibromomethane. (b) All new compounds have been fully characterized by their spectral and analytical data. Details will be reported in a full paper.

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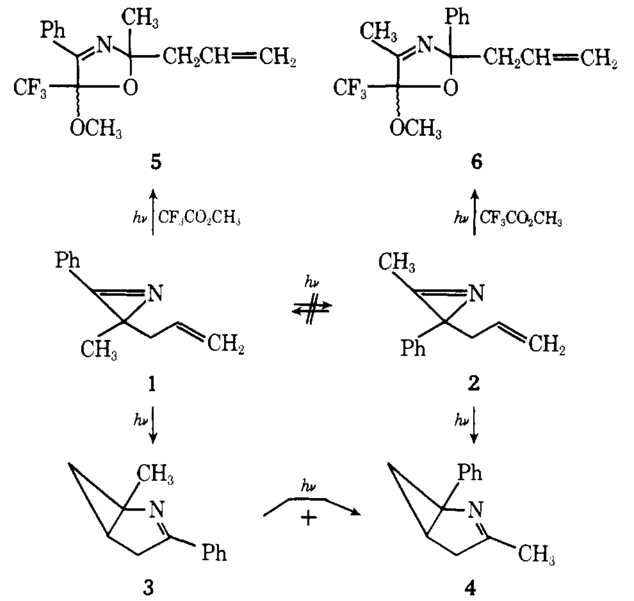
A Stepwise 1,3-Dipolar Cycloaddition Reaction[1]

Sir:

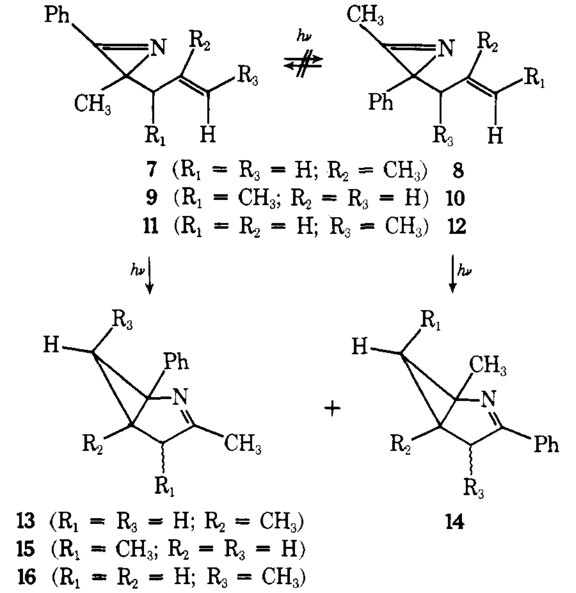
Substituted $2H$-azirines undergo photochemical ring opening to form nitrile ylides.[2,3] These 1,3-dipoles can be intercepted with a variety of dipolarophiles to produce five-membered heterocyclic rings.[2,3] Salem has recently carried out some ab initio computations on the ground and excited state energy surfaces of the $2H$-azirine molecule.[4] His calculations indicate that the ring-opened intermediate should be capable of dual reactivity when it is intercepted by an added dipolarophile. The behavior of the system was predicted to be dependent on the geometry of the transient intermediate generated from the photolysis. Opening of the ring to an intermediate with linear geometry will result in the formation of a 1,3-dipolar like species having closed-shell zwitterionic character. All of the photocycloadditions observed to date are in accord with such a species.[2,3] Salem's calculations also indicate that if the ring is opened to give an intermediate with bent geometry, a diradical state with partial dipolar character will be obtained. We now wish to report evidence which corroborates Salem's calculations and which also provides the first example of a stepwise 1,3-dipolar cycloaddition reaction.[5]

We recently reported that the irradiation of 2-phenyl-3-methyl-3-allylazirine (**1**) produced 2-azabicyclo[3.1.0]hex-2-ene (**4**) via an unusual 1,1-cycloaddition reaction[6] (Scheme I). In order to probe the generality of this internal cycloaddition reaction, we have examined the photochemical behavior of the isomeric 2-methyl-3-phenyl-3-allylazirine (**2**) system.[7] Irradiation of **2** in cyclohexane afforded a quantitative yield of azabicyclohexene (**4**). A control experiment showed that **1** and **2** were not interconverted by a Cope reaction under the photolytic conditions. Photolysis of **2** in the presence of the very reactive dipolarophile, methyl trifluoroacetate,[8] resulted in the trapping of a nitrile ylide and gave cycloadduct **6** in high yield.[9] Under these conditions, the formation of **4**, which is produced in quantitative yield in the absence of a trapping agent, is entirely suppressed. Photocycloaddition of **1** with added methyl trifluoroacetate resulted in the formation of cycloadduct **5** in high yield.[10] The isolation of **6** in the external trapping experiment eliminates a path by which **2** is partially isomerized to **1** which then rearranges to **4** on further excitation. This possibility was initially considered to be a reasonable one since the extinction coefficient of **1** at 254 nm (ϵ 8700) is much larger than that of **2** (ϵ 220). We have also found that the short term irradiation of **1** (20% conversion) produces a 1:1 mixture of azabicyclohexenes **3** and **4**.[11] On further irradiation, **3** was quantitatively isomerized to **4**. No significant quantities of **3** were found in the irradiation of **2**, however. This is probably related to the fact that **3** possesses a much larger extinction coefficient than **2** and is optically pumped to **4**, even at low conversions.

Scheme I

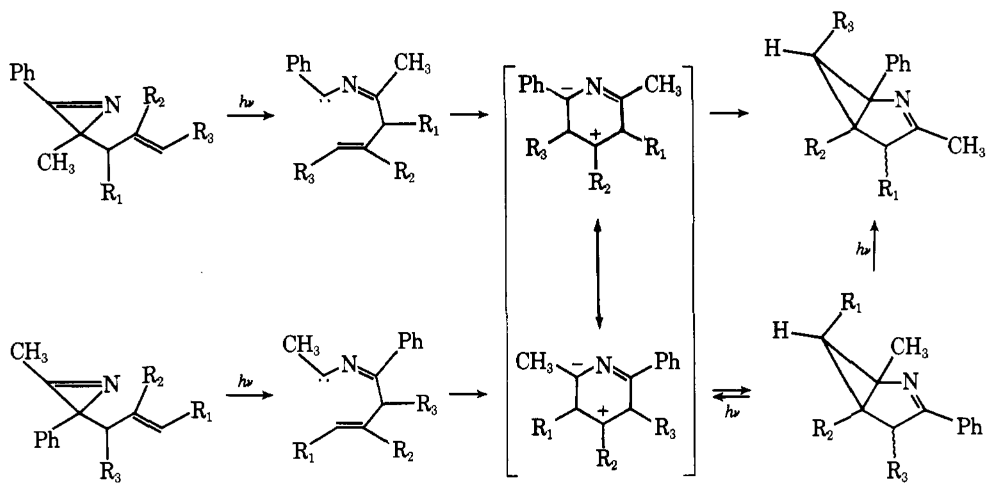


Scheme II



Support for this contention was obtained from a study of

Scheme III



the photobehavior of azirines **7** and **8** (Scheme II). Irradiation of **7** in cyclohexane for short periods of time (40% conversion) produced a mixture (4:1) of azabicyclohexenes **13** and **14** in quantitative yield.[12] A short term photolysis (40% conversion) of the isomeric 2-methylazirine system (**8**) afforded the same two photoproducts (i.e., **13** and **14**). On further irradiation, **14** was converted into **13**. When *E*-2-methyl-3-phenyl-3-(2-butenyl)azirine (**10**) was irradiated in cyclohexane (100% conversion), a mixture of the endo (25%) and exo (75%) isomers of 1-phenyl-3,4-dimethyl-2-azabicyclo[3.1.0]hex-2-ene (**15**) were the only products formed. This same epimeric mixture of isomers was produced from azirine **9**. We previously reported that the photolysis of azirine **11** gave azabicyclohexene **16**.[6] The formation of the thermodynamically less favored endo isomer from the trans olefin corresponds to a complete inversion of stereochemistry about the C–C double bond in the cycloaddition process. We now find that the thermodynamically less favored endo isomer (**16**) is also formed from the irradiation of azirine **12**.[13]

The most reasonable explanation to account for the observed cycloadditions involves a bent nitrile ylide intermediate (carbene-like) (Scheme III). Attack of the carbene carbon on the terminal position of the neighboring double bond will generate a six-membered ring dipole which contains a secondary carbonium ion as well as an aza-allyl anion portion. Collapse of this new 1,3-dipole will result in the formation of the observed azabicyclohexene system. The photoconversion of the azabicyclohexenes (i.e., **14** → **13**) can also be rationalized in terms of a six-membered ring dipole.

All of the 1,3-dipolar cycloadditions which have been subjected to mechanistic scrutiny follow concerted pathways as measured by the criteria of stereochemistry, solvent effects, and isotope effects.[14] Huisgen has suggested that these concerted 1,3-dipolar additions proceed via a "two-plane" orientation complex in which the dipole and dipolarophile approach each other in parallel planes.[15] A symmetry–energy correlation diagram reveals that such a cycloaddition is an allowed process.[16] With the above allylazirines, however, the normal "two-plane" orientation approach of the linear nitrile ylide and the allyl π-system is impossible as a result of the geometric restrictions imposed on the system. Product formation is possible if the linear nitrile ylide undergoes rehybridization to give a species of bent geometry. Once this occurs, the cycloaddition reaction is no longer concerted and instead proceeds by a stepwise-diradical (or zwitterionic) intermediate.[17]

Further evidence for the involvement of two different geometric forms of a nitrile ylide was obtained from competitive rate studies. Linear nitrile ylides react preferentially with electron-deficient alkenes, since such a pair of addends possesses a narrow dipole-HOMO dipolarophile-LUMO gap.[18] This is the case when the above allyl substituted azirines undergo cycloaddition with external dipolarophiles. Thus, fumaronitrile undergoes cycloaddition at a much faster rate (ca. 189 000) than methyl crotonate and aliphatic olefins were found to be ineffective dipolarophiles. A study of the quantum yield for azabicyclohexene formation as a function of added dipolarophile shows, however, that the internal photocyclization of the allyl azirine system occurs readily with these aliphatic substituted olefins.[19] This is consistent with the bent nitrile ylide form since carbenes are known to react rapidly with electron-rich double bonds.[20]

We are continuing to explore the scope and mechanistic features of this novel cycloaddition reaction and will report additional findings at a later date.

Acknowledgment. We gratefully acknowledge support of this work by the National Institutes of Health (Grant CA-12195-09) and the National Science Foundation (Grant PO-37550).

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(7) Azirine **2** was prepared by a modified Neber reaction in which 3-phenyl-hex-5-en-2-one was treated with dimethylhydrazine according to the general procedure of N. J. Leonard and B. Zwanenburg, *J. Am. Chem. Soc.*, **89**, 4456 (1967). This same approach was used to prepare azirines **8**, **10**, and **12**. Complete spectroscopic properties of the unsaturated azirines will be given in our full publication.

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(9) Compound **6**: ir (neat) 2920, 2840, 1660, 1440, 1430, 1335, 1260, 1170 cm^{-1}; uv (hexane) 236 nm; NMR (CCl_4) τ 7.92 (3 H, s), 7.42 (2 H, d, $J = 6.0$ Hz), 7.20 (3 H, s), 5.0–5.4 (m, 2 H), 4.2–4.8 (m, 1 H), 2.5–2.9 (m, 5 H); *m/e* 258 (M^+), 230, 155, 119, 117, 195, 104.

(10) Compound **5**: ir (neat) 2920, 2840, 1625, 1445, 1180, 1075 cm^{-1}; uv

(hexane) 248 nm; NMR (CCl_4) equal mixture of two stereoisomers τ 8.54 (s, 3 H), 7.56 (d, 2 H, J = 6.0 Hz), 6.68 (s, 3 H), 4.84–5.17 (m, 2 H), 3.90–4.56 (m, 1 H), 2.8–3.1 (m, 3 H), 2.2–2.45 (m, 2 H), and 2d isomer τ 8.45 (s, 3 H), 7.42 (d, 2 H, J = 6.0 Hz), 6.64 (s, 3 H), 4.84–5.17 (m, 2 H), 3.90–4.56 (m, 1 H), 2.8–3.1 (m, 3 H), 2.2–2.45 (m, 2 H); *m/e* 258 (M^+), 217, 189, 105, 104.

(11) Compound **3:** NMR (CCl_4) τ 9.92 (t, 1 H, J = 5.0 Hz), 9.10 (dd, 1 H, J = 8.0 and 5.0 Hz), 8.20 (m, 1 H), 8.38 (s, 3 H), 7.60 (d, 1 H, J = 17.5 Hz), 6.78 (dd, 1 H, J = 17.5 and 8.0 Hz), 2.61–3.10 (m, 5 H); compound **4,** see ref 6.

(12) Compound **13:** NMR (CCl_4) τ 9.58 (d, 1 H, J = 5.0 Hz), 8.95 (s, 3 H), 8.59 (d, 1 H, J = 5.0 Hz), 8.06 (s, 3 H), 7.38 (br s, 2 H), 2.5–3.0 (m, 5 H). Compound **14:** NMR (CCl_4) τ 9.80 (d, 1 H, J = 5.0 Hz), 9.38 (d, 1 H, J = 5.0 Hz), 8.74 (s, 3 H), 8.52 (s, 3 H), 7.38 (br s, 2 H), 2.5–3.0 (m, 5 H).

(13) Photolysis of 2-phenyl-3-methyl-*Z*-3-(2-butenyl)azirine also results in the exclusive formation of *endo*-azabicyclohexene **16.** These stereochemical results can now be rationalized by assuming that the collapse of the initially formed six-membered ring dipole to the thermodynamically more favored exo isomer results in a severe torsional barrier. Formation of the endo isomer (i.e., **16**), however, moves the phenyl and methyl groups further apart and is the kinetically preferred process.

(14) R. Huisgen, *Angew. Chem., Int. Ed. Engl.,* **2,** 565 (1973); *ibid.,* **2,** 633 (1963); R. Huisgen, R. Grashey, and J. Sauer in "The Chemistry of Alkenes", S. Patai, Ed., Interscience, New York, N.Y., 1964, pp 806–878.

(15) R. Huisgen and H. Gotthardt, *Chem. Ber.,* **101,** 1059 (1968).

(16) A. Eckell, R. Huisgen, R. Sustmann, G. Wallbillich, D. Grashey, and E. Spindler, *Chem. Ber.,* **100,** 2192 (1967).

(17) It should be pointed out that the mechanism proposed here to account for the formation of the azabicyclohexenes is very similar to Firestone's stepwise diradical mechanism.[5]

(18) K. N. Houk, *Acc. Chem. Res.,* **8,** 361 (1975).

(19) From the slope and intercept of the Stern-Volmer analysis for azabicyclohexene formation in the presence of a given dipolarophile, the ratio of the external to internal rate constants for cycloaddition of the nitrile ylide can be determined. Since the rate constants for reaction of different nitrile ylides with a particular dipolarophile are almost identical,[2] the ratio slopes/intercepts of different allylazirines will give the relative rates of internal cyclization as a function of substitution about the C-C double bond.

(20) W. Kirmse in "Carbene Chemistry", Academic Press, New York, N.Y., 1964.

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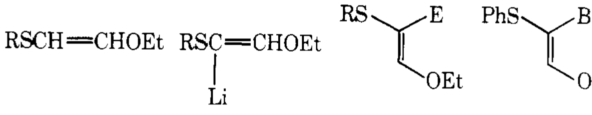
Preparation and Reactions of 2-(Alkoxy)-1-(alkyl or arylthio)vinyllithium. Application in the Synthesis of 9-Desoxo-9-thiaprostaglandins

Sir:

The reaction of a cis-trans mixture of 2-(ethoxy)-1-(pentyl or phenylthio)ethylenes (**1a,b**)[1] with *tert*-butyllithium in THF at −70° for 1 h results in essentially quantitative formation of the 2-(ethoxy)-1-(pentyl or phenylthio)-vinyllithium (**2a,b**). Although, under similar conditions, vinyl sulfides[2] and vinyl ethers[3] are converted to the corresponding 1-vinyllithium derivatives in high yields, the lithiation of **1a,b** occurs regioselectively at C_1. Evidence for the regioselective lithiation is provided by the reactions of the anion **2** with electrophiles (E^+) to produce exclusively products such as **3**[4] (Table I). Alternatively, the anion **2a** is prepared quantitatively by treatment of 1-(bromo)-2-(ethoxy)-1-(phenylthio)ethylene (**4**)[5] with *n*-butyllithium (1 equiv) in ether[6] at −70° for 0.5 h.[7]

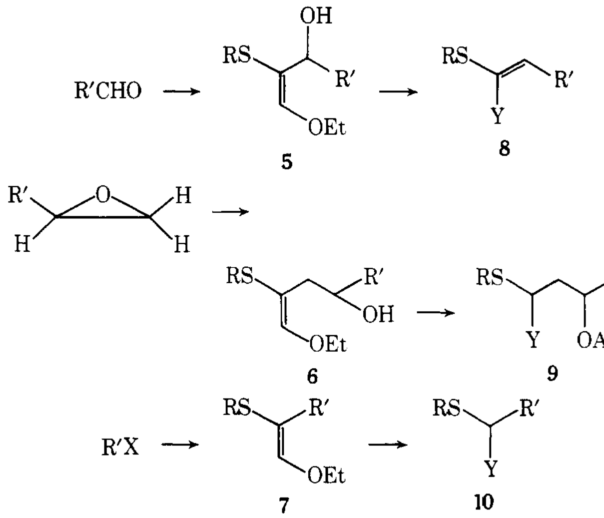


1 2 3 4

a, R = Ph b, R = n-C_5H_{11}

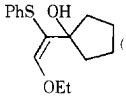
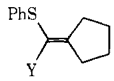
At −70°, the anion **2** reacts smoothly with aldehydes and ketones to produce the allylic alcohols **5**[8] in excellent yields (Scheme I). Under acidic (aqueous HCl, THF, 5 min, 0°) or weakly basic ($SOCl_2$–pyridine, ether-hexane, −20°) conditions, these substances undergo facile rearrangements[9] to produce α-mercapto-α,β-unsaturated aldehydes **8** (Y =

Scheme I



Y = CHO or $CH(OEt)_2$

Table I. Reaction of 2-(Ethoxy)-1-(pentyl or phenylthio)vinyllithium with Electrophiles

RSCH=CHOEt		Adduct (yield %)[a]		Rearrangement or solvolysis product[e]	
R	Electrophile	R	R′	R	R′
Ph	Benzaldehyde	5 Ph	Ph (75)[c,j]	8 Ph	Ph[f]
n-C_5H_{11}	Benzaldehyde	5 n-C_5H_{11}	Ph (80)[c,j]	8 n-C_5H_{11}	Ph[f]
Ph	Cyclopentanone		 (78)[b,c]		 [f]
Ph	Crotonaldehyde	5 Ph	—CH=CHCH$_3$ (78)[b,c]	8 Ph	—CH=CHCH$_3$[f,j]
Ph	Heptanal	5 Ph	n-C_6H_{13} (84)[c,j]	8 Ph	n-C_6H_{13}[f,g,j]
n-C_5H_{11}	Heptanal	5 n-C_5H_{11}	n-C_6H_{13} (82)[b,c]	8 n-C_5H_{11}	n-C_6H_{13}[f]
Ph	Ethylene oxide	6 Ph	H (60)[c,j]	9 Ph	H[h,i]
Ph	Propylene oxide	6 Ph	CH_3 (55)[d,j]		
Ph	1-Iodobutane	7 Ph	n-C_4H_9 (55)[d,j]		
n-C_5H_{11}	1-Bromobutane	7 n-C_5H_{11}	n-C_4H_9 (42)[d,j]	10 n-C_5H_{11}	n-C_4H_9[h]
n-C_5H_{11}	1-Iodobutane	7 n-C_5H_{11}	n-C_4H_9 (60)[d]		

[a] Unless otherwise indicated the yields were based on products isolated by preparative TLC. [b] The yields were determined by spectral data of the crude products. These adducts were subjected to rearrangement reactions without purification. [c] Reaction in THF. [d] Reaction in THF/HMPA. [e] Unless otherwise indicated, all rearrangements and solvolyses proceeded in 85–90% yields. [f] Rearrangement with 1 N aqueous HCl in THF at 0° for Y = CHO and with p-TsOH in ethanol at 0° for Y = $CH(OEt)_2$. [g] Rearrangement with $SOCl_2$ and pyridine in ether–hexane at −20° for Y = CHO. [h] Solvolysis with aqueous AcOH at 50° for Y = CHO and with p-TsOH in ethanol for Y = $CH(OEt)_2$. [i] Solvolysis proceeded in 40–50% yield. [j] Reference 17.