(9) P. Aymonino, *Photochem. Photobiol.*, 7, 761 (1968).
(10) E. J. Ariëns, "Drug Design", Vol. 2, E. J. Ariëns, Ed., Academic Press, New York, N.Y., 1971, p 2.
(11) L. Stryer, "Biochemistry", W. H. Freeman, San Francisco, Calif., 1975, pp 754–766.
(12) Proposals [J. T. Park, *Symp. Soc. Gen. Microbiol.*, 49–61 (1958)] as well as experimental—albeit sporadic—attempts [B. Cavalleri, E. Bellasio, and E. Testa, *Gazz. Chim. Ital.*, **96**, 253 (1966)] were made to discover novel antibacterials on related grounds, employing in essence the widely recognized antimetabolite approach (A. Albert, "Selective Toxicity", 5th ed, Chapman and Hall, London, 1973, pp 243–81).
(13) H. J. Rogers and H. R. Perkins, "Cell Walls and Membranes", Spon Ltd., London, 1968 pp 214, 220, 261.
(14) P. D. Hoeprich, *J. Biol. Chem.*, **240**, 1654 (1965).
(15) J. Mandelstam and K. McQuillen, Ed., "Biochemistry of Bacterial Growth", 2d ed, Wiley, New York, N.Y., 1973, p 88.
(16) Interference with bacterial synthesis of D-alanine via racemization of L-alanine [J. L. Strominger, E. Ito, and R. H. Trenn, *J. Am. Chem. Soc.*, **82**, 998 (1960)] and suppression of incorporation of D-alanine into peptidoglycan—by inhibition of formation of the required D-alanyl-D-alanine intermediate—has been shown instrumental in mechanism of activity of cycloserine [F. C. Neuhaus and J. L. Lynch, *Biochemistry*, **3**, 471 (1964)]. A key step in the bacterium-killing mechanism of β-lactam antibiotics (penicillins, cephalosporins) involves inhibition of transpeptidation, releasing D-alanine [J. L. Strominger, *Harvey Lect.*, **64**, 179 (1970)].
(17) J. Kollonitsch, L. Barash, F. M. Kahan, and H. Kropp, *Nature*, **243**, 346 (1973).
(18) J. Kollonitsch, U.S. Patent 3 839 170 (1974), and U.S. Patent 3 956 367 (1976).
(19) J. Kollonitsch, L. Barash, N. P. Jensen, F. M. Kahan, S. Marburg, L. Perkins, S. M. Miller, and T. Y. Shen, Abstracts, 15th Interscience Conference on Antimicrobial Agents and Chemotherapy, Washington, D.C., Sept 1975, No. 102.
(20) F. M. Kahan, H. Kropp, H. R. Onishi, and D. P. Jacobus, ref 19, Abstract No. 103.
(21) N. P. Jensen, U.S. Patent 3 932 439 (1976).
(22) F. M. Kahan and H. Kropp, Abstracts, 15th Interscience Conference on Antimicrobial Agents and Chemotherapy, Washington, D.C., Sept 1975, No. 100.
(23) H. Kropp, F. M. Kahan, and H. B. Woodruff, ref 22, Abstract No. 101.
(24) The reactors have been designed and built with the cooperation of Mr. R. Geiger.
(25) J. P. Greenstein and M. Winitz, "Chemistry of Amino Acids", Vol. 3, Wiley, New York, N.Y., 1961, p 1831.
(26) E. Ito and J. L. Strominger, *J. Biol. Chem.*, **237**, 2689 (1962).
(27) J. Kollonitsch and F. M. Kahan, German Patent Application No. 2 136 067; *Chem. Abstr.*, **76**, 100053g (1972).
(28) Kel-F reactor with a volume of ~700 ml was employed. For design, see ref 7.
(29) This and other improvements in scaling up the method up to 1 g mol of D-alanine were contributed by Dr. S. Marburg and Mr. L. M. Perkins of these laboratories.
(30) Note: About other products of photofluorination of alanine, see our forthcoming paper (manuscript under preparation).

Stable Fluorinated Cyclobutenyl Cations

B. E. Smart* and G. S. Reddy

Contribution No. 2357 from the Central Research and Development Department,
E. I. du Pont de Nemours and Company, Experimental Station, Wilmington,
Delaware 19898.

Received February 19, 1976

Abstract: A series of remarkably stable 1-methoxy-2-R-3,4,4-trifluorocyclobutenyl cations (**2**, R = F, Cl, OCH$_3$) have been prepared and studied by ^{1}H and ^{19}F NMR. The hexafluoroantimonate salts of **2** are isolable solids which are stable at room temperature. In solution, each cation exists as an equilibrating pair of isomers which differ only by the 1-methoxy group conformation. From a complete line-shape analysis of the temperature-dependent ^{1}H NMR, $\Delta G^{\ddagger} = 16.4$ kcal/mol for the barrier to rotation of the methoxy group in **2** (R = F); similarly, $\Delta G^{\ddagger} = 15.9$ and 15.7 kcal/mol for **2** (R = Cl) and **2** (R = OCH$_3$), respectively. The NMR data also establish the importance of 1,3-π overlap in these cations. The cyclobutenyl cations are excellent alkylating agents which can be employed in the synthesis of novel fluorinated cyclobutenones.

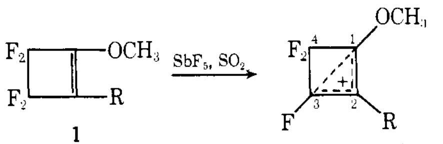
Both acyclic and cyclic allyl carbocations are now a class of well-characterized stable ions.[1] Although stable polyhalogenated allyl cations, e.g., the perchloroallyl ion,[2] have been studied, most attempts to generate stable polyfluoroallyl cations have been unsuccessful. Hexafluorocyclobutene is inert to SbF$_5$-SO$_2$ClF at −10 °C[3] and hexafluoropropene reacts with SbF$_5$ to give a product proposed to arise by an electrophilic dimerization, but no long-lived cations are observed.[4] To our knowledge, the 1-anisyl tetrafluoroallyl cation studied by Chambers and co-workers[4] is the only reported long-lived polyfluoroallyl cation.

In carbocations it is now well established that fluorine is conjugatively stabilizing when substituted at the cation center, but is destabilizing when substituted at adjacent or further removed positions. Apparently the fluorine inductive effect dominates conjugative stabilization and results in net destabilization of perfluoroallyl cations. A substituent which can further conjugatively stabilize positive charge, e.g., the anisyl group, is required for polyfluoroallyl cation stability.

We report here our results concerning the reaction of SbF$_5$ with 1-methoxy polyfluorinated cyclobutenes. The methoxy substituent is anticipated to provide the necessary stabilization required for reactivity and carbocation stability. Furthermore, the cyclobutenyl cations produced may further benefit from 1,3-π participation not available to their acyclic counterparts. The importance of 1,3-π overlap in hydrocarbon cyclobutenyl cations has been thoroughly examined by Olah and co-workers.[1b]

Results

1. Ion Production and NMR Spectra. The cyclobutenes **1** readily react with SbF$_5$ in SO$_2$ at −78 to −10 °C to produce the cyclobutenyl cations **2**.



1

2(R = F, Cl, OCH$_3$)

The ^{19}F and ^{1}H NMR spectra of these cations at low temperature (−35 °C) indicate the presence of two isomeric species in each case (Table I). For example, at −35 °C the 1-methoxy-2-chlorotrifluorocyclobutenyl cation (**2**, R = Cl) shows a broad singlet at δ 5.22 and poorly resolved doublet ($J \simeq 0.5$ Hz) at δ 5.07. The ^{19}F NMR spectrum consists of two sets of multiplets; a 8.8-Hz triplet (1 F) at ϕ −24.8 and a 8.8-Hz doublet (2 F) at ϕ −104.6, and a 8.4-Hz triplet (1 F) at ϕ −26.4 and a 8.4-Hz doublet (2 F) at ϕ −98.1. The isomers are present in approximately equal amounts (determined by integration of the ^{1}H and ^{19}F NMR signals). Both the ^{1}H and ^{19}F NMR spectra are temperature dependent; upon warming

Table I. H and ^{19}F NMR Data for the Isomeric Pairs of Cyclobutenyl Cations[a]

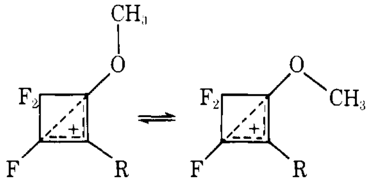
	Chemical shifts (multiplicities, coupling constants)			
Ion (isomer)[b]	C(1) substituent	C(2) substituent	C(3) substituent	C(4) substituent
2 (R = F)				
(Major)	5.04 (t, 0.6)	−99.7 (dt, 15.2, 12.1)	−34.9 (dt, 15.2, 9.2)	−105.8 (dd, 12.1, 9.2)
(Minor)	4.97 (t, ~0.5)	−100 (m)[c]	−36.6 (dt, 14, 7)	−100 (m)[c]
2 (R = Cl)				
(Major)	5.22		−24.8 (t, 8.8)	−104.6 (d, 8.8)
(Minor)	5.07 (d, ~0.5)		−26.4 (t, 8.4)	−98.1 (d, 8.4)
2 (R = OCH_3)				
(Major)	4.79 (d, 0.8)	4.02 (m)	−51.2 (tm, 10.9)	−102.4 (dm, 10.9)
(Minor)	4.70	4.05 (m)	−49.8 (tm, 10.7)	−95.5 (dm, 10.7)

[a] ^{1}H chemical shifts are in parts per million (ppm) relative to external tetramethylsilane; ^{19}F chemical shifts in ppm relative to external trichlorofluoromethane. All spectra was taken at −35 °C in SO_2. Signals are unresolved singlets unless shown, d = doublet, t = triplet, m = multiplet. [b] Isomer ratios are 69:31 (R = F), 52:48 (R = Cl), 67:33 (R = OCH_3). [c] Approximate value. Not determined accurately owing to overlap of fluorine multiplets.

the sample to 55 °C the ^{1}H resonances coalesce and finally emerge as a broad singlet at δ 5.12 (Figure 2), while the ^{19}F multiplets gradually broaden and finally begin to merge into the base line. The sample decomposes when heated further (since the exchange rate at coalescence for a two-site exchange process is approximately proportional to the differences of the individual site resonance frequencies, the coalescence temperature for the fluorine resonances will be unaccessibly high). These processes are completely reversible and lowering the sample temperature regenerates the original spectra.

Cations **2** (R = F) and **2** (R = OCH_3) similarly are mixtures of isomers, 67:33 and 65:35 (±2%), respectively, and exhibit temperature-dependent ^{1}H NMR (Figures 1 and 3) and ^{19}F NMR spectra. Further cooling of the spectra (**2,** R = F, Cl, OCH_3) to −78 °C effected only slight viscosity broadening of the proton and fluorine resonances. There was no evidence for nonequivalent C(4) geminal fluorines in any of the cation isomers **3a** and **3b** in the temperature range studied. Solubility difficulties prevented spectral observations at lower temperatures.

We conclude from these NMR data that each cation exists in solution as an equilibrating isomeric pair which differs by the conformation of the 1-methoxy group (**3a** ⇌ **3b**). It is not



3a **3b**

possible at this time to assign the specific isomer structures, although on steric grounds structure **3a** should be favored over **3b**.

A complete line-shape analysis of the temperature-dependent ^{1}H NMR spectrum of each cation was achieved by direct comparison of the observed spectra with the calculated spectra[5] (Figures 1–3). The rate constants obtained for the methoxy-group rotations were converted to $\Delta G^{\ddagger}$ values by the Eyring equation. The following $\Delta G^{\ddagger}$ values thus were obtained: **2** (R = F) = 16.4; **2** (R = Cl) = 15.9; **3** (R = OCH_3) = 15.7 kcal/mol.

In each case the cations are quite stable in SO_2 and their solutions can be heated to ca. 50 °C without appreciable decomposition. If the SO_2 solvent is evaporated in an inert atmosphere, the cation salts are deposited as crystalline solids. These salts are indefinitely stable at room temperature if moisture is rigorously excluded. With the exception of some fluorinated cyclopropenium hexafluoroantimonates,[6] these are the only examples of isolable polyfluorocation salts which exhibit such stability.

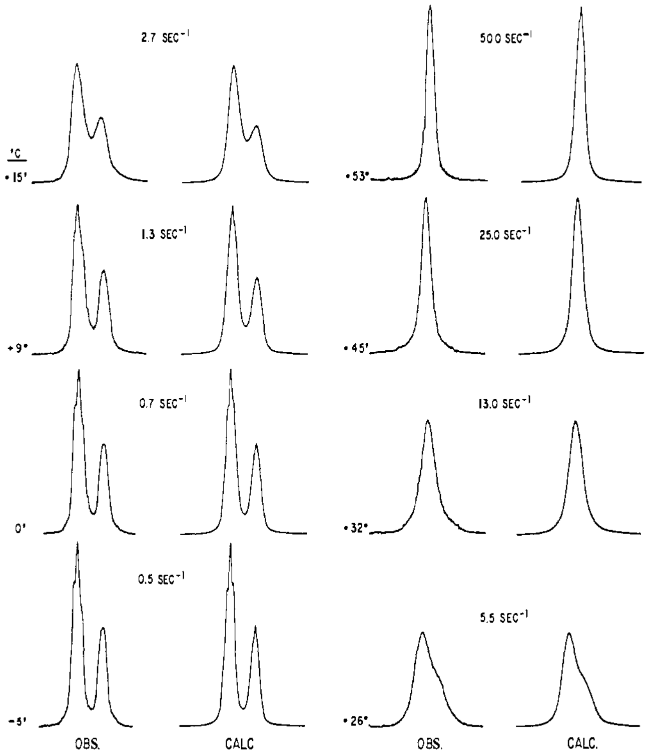


Figure 1. Experimental and calculated 60-MHz ^{1}H NMR spectra of the methoxytetrafluorocyclobutenyl cation (**2,** R = F).

The cations also can be prepared by adding **1** to neat SbF_5 while keeping the temperature below ca. 40 °C. However, this procedure is not recommended, since the cation salts precipitate from the reaction mixture during addition and interfere with efficient mixing.

When **1** (R = OCH_3) was treated with ≥2 equiv of SbF_5 at −10 °C, only **2** (R = OCH_3) was detected and there was no evidence for the dimethoxydifluorocyclobutenyl dication.

In contrast to the cyclobutenyl ethers **1**, *cis*- or *trans*-2-methoxyheptafluorobut-2-ene, an approximate acyclic analogue of **1** (R = F), did not react with SbF_5–SO_2 at −10 °C.

2. Ion Reactions. The isolated ion salts are hydrolytically quite unstable and can be quenched in water to give novel cy-

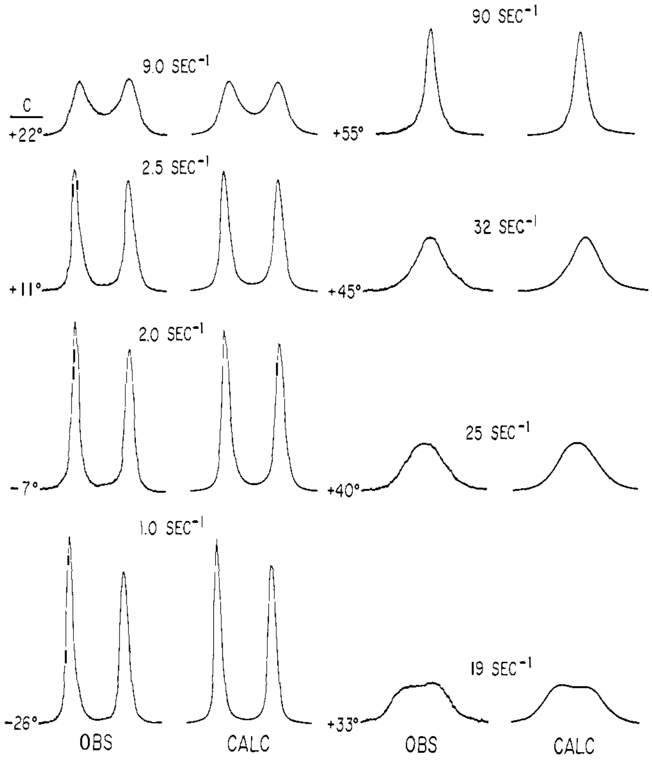
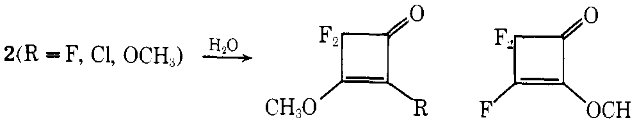


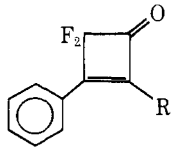
Figure 2. Experimental and calculated 60-MHz ^1H NMR spectra of the 1-methoxy-2-chlorotrifluorocyclobutenyl cation (**2**, R = Cl).

clobutenones **4**. When hydrolyzed, **2** (R = F) and **2** (R = Cl) gave **4** (R = F) and **4** (R = Cl) in 45 and 53% isolated yields, respectively. A mixture of 54% **4** ($R = OCH_3$) and 46% **5** in 46% overall isolated yield resulted when **2** ($R = OCH_3$) was hydrolyzed.



4(R = F, Cl, OCH₃) 5

The cation salts also are excellent alkylating agents in electrophilic substitution reactions. For example, **2** (R = F) and **2** (R = Cl) readily react in SO_2 with benzene to give the cyclobutenones **6** (R = F, Cl) in 67 and 77% isolated yields, respectively, after hydrolytic workup.



6(R = F, Cl)

When the cation salt **2** (R = F) was gradually heated, it melted with foaming at 60-80 °C and rapidly decomposed at 80-90 °C. Hexafluorocyclobutene was isolated in 52% yield along with a trace of tetrafluorocyclobutenone.[7] A similar pyrolysis of **2** ($R = OCH_3$) gave methyl fluoride, but no other products were isolated.

Discussion

The appreciable deshielding (63-94 ppm) of the fluorine atoms at C(3) when compared with the precursor cyclobutenyl ether resonances (Table II) is cogent evidence that free cyclobutenyl cations have been generated.

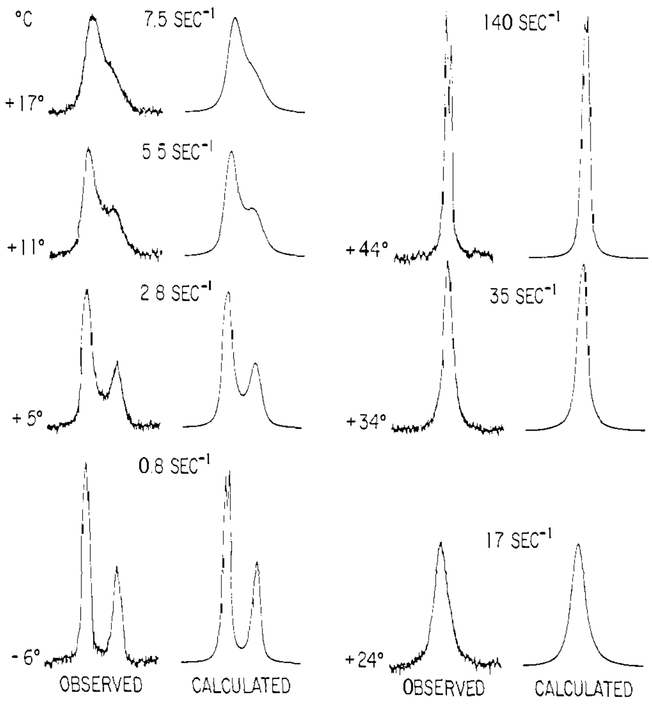


Figure 3. Experimental and calculated 60-MHz spectra of the 1,2-dimethoxytrifluorocyclobutenyl cation (**2**, $R = OCH_3$). (Only the downfield 1-methoxy group is shown.)

Table II. ^{19}F and ^1H Isomeric Cation Deshieldings in SO_2[a]

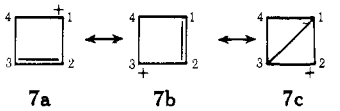
Ion (isomer)	C(1) substituent	C(2) substituent	C(3) substituent	C(4) substituent
2 (R = F)				
(Major)	1.0	43.9	84.9	11.4
(Minor)	0.9	~44	83.5	~17
2 (R = Cl)				
(Major)	1.1		93.7	13.4
(Minor)	0.9		92.1	19.9
2 ($R = OCH_3$)				
(Major)	0.9	0.1	62.6	11.4
(Minor)	0.8	0.1	64.0	18.3

[a] All values in parts per million downfield relative to carbon substituent in un-ionized cyclobutenyl ether **1**.

The observed high activation barrier to methoxy rotation in these ions confirms the substantial conjugative interaction of the oxygen lone-pair electrons with positive charge generated at C(1).[8] This interaction must contribute appreciably to the stability of these ions.

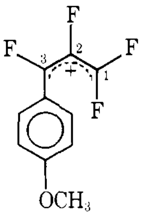
However, the somewhat surprising result that 2-methoxyheptafluorobut-2-ene does not react under the same conditions employed for **1** (R = F) suggests some additional stabilization is available to the cycloalkenyl ion, but not to the acyclic alkenyl ion, namely, 1,3-π interaction.

The cyclobutenyl cation can be represented as a hybrid of the classical forms **7a** ↔ **7b** and the 1,3-π overlap hybrid **7c**. While there is both definitive theoretical and experimental evidence for 1,3-π participation in the cyclobutenyl system, there is no evidence for such participation in acyclic alkenyl cations.[1b]



7a **7b** **7c**

The question of 1,3-π participation in cations **2** can be examined along several lines. If form **7c** is important, the positive charge developed at C(2) should result in deshielding of the C(2) fluorine resonance on ionization. In fact, this resonance is deshielding by ca. 44 ppm (Table II). This value is particularly striking when compared to the effects observed in cation **8**.[4]



8

While the C(3) fluorine signal is deshielded by 94 ppm from its position in the un-ionized olefin (*trans*-1-anisylpentafluoropropene), the C(2) fluorine signal is *shielded* by 6 ppm. Clearly, ion **8** exhibits only classical allyl cation resonance, whereas 1,3-π overlap must be invoked to explain the appreciable downfield shift of the C(2) fluorine on ionization of **1** (R = F).

It is known that the importance of hybrid form **7c** increases as conjugatively stabilizing substituents are introduced at C(2), but decreases as such substituents are placed at C(1) or C(3).[1b] The consequence of placing increasingly stabilizing substituents at C(2) is to decrease the contribution of hybrid forms **7a** and **7b** and, hence, decrease positive charge at C(1) and C(3). Within the series of cations **2** (R = F, Cl, OCH_3), the C(1) and C(3) substituents remain constant and the effect of varying the C(2) substituent can be evaluated.

The deshielding of the C(3) fluorine signals decreases from 94 to 63 ppm (Table II), hence, the positive charge at C(3) decreases in the order of C(2) substitution, R = OCH_3 < F < Cl. This is exactly the order of stability expected for **7c** with this C(2) substitution pattern. These results further support 1,3-π interaction in **2** and this interaction is expectedly most favorable when R = OCH_3.

Although we have demonstrated enhanced charge density of C(2) in ions **2** (R = OCH_3, F, Cl), we cannot rigorously define the nature of the 1,3 overlap. We have assumed planar cyclobutenyl ions with varying degrees of 1,3-π overlap depending upon the substitution pattern. The failure to observe nonequivalent C(4) geminal fluorines suggests that these ions do not exist as puckered homoaromatic species (1,3 overlap involving a bonding intermediate between the σ and π type).[9] However, we cannot conclusively rule out bent cations with low-energy barriers to inversion or both homoaromatic and planar components of comparable energy in dynamic equilibrium.

Experimental Section

The ^1H and ^{19}F NMR spectra were obtained on a Varian Associates Model A 56/60 spectrometer equipped with variable temperature accessories. The proton chemical shifts in SO_2 are referred to external tetramethylsilane; the fluorine chemical shifts are referred to external trichlorofluoromethane. Spectra in CCl_4 are referred to internal standards. All melting and boiling points are uncorrected.

The cyclobutenyl ethers **1** (R = F, Cl, OCH_3) are reported compounds[10-12] and slightly modified, consonant synthetic procedures are presented below.

1-Methoxypentafluorocyclobutene (1, R = F). A solution of 54 g (1 mol) of sodium methoxide in 500 ml of dry methanol was added dropwise to 162 g (1.0 mol) of hexafluorocyclobutene chilled to −10 to −15 °C in a wet ice/acetone bath. After stirring overnight at room temperature, the reaction mixture was quenched in 1.5 l. of cold water. The organic layer was withdrawn and the aqueous phase was extracted with methylene dichloride. The combined organics were washed with saturated sodium chloride, dried ($MgSO_4$), and distilled to give 121 g (70%) of **1** (R = F): bp 87–88 °C (lit.[10] bp 87 °C (747 mm)); ir (neat) 1765 cm^{-1} (C=C); NMR (SO_2, ext ref) ^1H δ 4.04 (d, J = 1.5 Hz), ^{19}F ϕ −117.2 (m, 2), −119.8 (m, 2), −143.6 (m, 1).

1-Methoxy-2-chlorotetrafluorocyclobutene (1, R = Cl). A solution of 60.0 g (0.308 mol) of 1,2-dichlorotetrafluorocyclobutene in 75 ml of methanol at room temperature was treated dropwise with a solution of 17.5 g (0.324 mol) of sodium methoxide in 175 ml of methanol. After the solution had been stirred for 4 h, the mixture was quenched in 600 ml of water, worked up as in the above procedure, and distilled to give 47.5 g (81%) of **1** (R = Cl): bp 62-63 °C (100 mm) (lit.[11] bp 117 °C); ir (neat) 1695 cm^{-1} (C=C); NMR (SO_2, ext ref) ^1H δ 4.15 (t, $J \simeq$ 0.5 Hz), ^{19}F ϕ −117.1 (m), −118.5 (m, 1).

1,2-Dimethoxytetrafluorocyclobutene (1, R = OCH₃). A solution of 1.0 mol of sodium methoxide in 500 ml of methanol chilled in a wet ice/acetone bath was treated slowly with 81 g (0.5 mol) of hexafluorocyclobutene. After 16 h at room temperature, the reaction mixture was worked up as before and distilled to afford 69.1 g (74%) of **1** (R = OCH_3): bp 68-71 °C (60 mm) (lit.[12] bp 36 °C (11 mm)); ir (neat) 1740 cm^{-1} (C=C); NMR (SO_2, ext ref) ^1H δ 3.92 (s), ^{19}F ϕ −113.8 (s).

Ion Preparations. Under anhydrous conditions, a solution of freshly distilled SbF_5 in SO_2 (ca. 2 M) at −78 to −40 °C was treated dropwise with 1 equiv of the respective cyclobutene **1** (R = F, Cl, OCH_3). The resulting homogeneous, colorless solutions were warmed to room temperature, while the SO_2 was removed in a slow stream of nitrogen. The hexafluoroantimonate salts **2** (R = F, Cl, OCH_3) were deposited as colorless, crystalline solids and were bottled under argon. The solutions for NMR study can be prepared by directly withdrawing samples from the reaction mixture or by redissolving the stock salts in SO_2.

3-Methoxy-2,4,4-trifluorocyclobut-2-en-1-one (4, R = F). The hexafluoroantimonate salt of **2** (R = F), 39 g (0.1 mol), was added cautiously in portions to vigorously stirred ice water. After the salt completely dissolved, 25 ml of methylene dichloride was added and the organic layer was withdrawn, washed with saturated sodium chloride, dried ($MgSO_4$), and distilled to give 6.9 g (45%) of **4** (R = F): bp 49 °C (5 mm); ir (neat) 1825 (C=O), 1680 cm^{-1} (C=C); NMR (CCl_4) ^1H δ 4.48 (d, $J \simeq$ 1.5 Hz), ^{19}F ϕ −115.4 (d, 2, J = 21.5 Hz), −124.3 (t of q, 1, J = 21.5, 1.5 Hz).

Anal. Calcd for $C_5H_3F_3O_2$: C, 39.49; H, 1.93; F, 37.48. Found: C, 39.59; H, 2.10; F, 38.34.

2-Chloro-3-methoxy-4,4-difluorocyclobut-2-en-1-one (4, R = Cl). The hexafluoroantimonate salt of **2** (R = Cl), 40.6 g (0.1 mol) was hydrolyzed and worked up as above to give 8.9 g (53%) of **4** (R = Cl): bp 62-63 °C (5 mm); ir (neat) 1804 (C=O), 1625 cm^{-1} (C=C), NMR (CCl_4) ^1H δ 4.48 (s), ^{19}F ϕ −113.2 (s).

Anal. Calcd for $C_5H_3ClF_2O_2$: C, 35.64; H, 1.79; F, 22.55. Found: C, 35.76; H, 1.90; F, 22.67.

2,3-Dimethoxy-4,4-difluorocyclobut-2-en-1-one (4, R = OCH₃) and 2-Methoxy-3,4,4-trifluorocyclobut-2-en-1-one (5). The hexafluoroantimonate salt of **2** (R = OCH_3), 40.2 g, (0.1 mol), was hydrolyzed to give 2.8 g of pure **5**: bp 49 °C (30 mm); ir (neat) 1810 (C=O), 1690 cm^{-1} (C=C); NMR (CCl_4) ^1H δ 4.23 (dt, $J \simeq$ 0.8, 0.6 Hz), ^{19}F ϕ −112.1 (narrow m, overlapping F); 0.4 g of 95% **5**: bp 34-39 °C (10-13 mm); 0.5 g of 80% **4** (R = OCH_3): bp 57-62 °C (3 mm); and 3.7 g of pure **4** (R = OCH_3): bp 52 °C (0.8 mm); ir (neat) 1798 (C=O), 1643 cm^{-1} (C=C); NMR (CCl_4) ^1H δ 4.15 (s, 1), 4.22 (s, 1), ^{19}F ϕ −111.4 (s).

Anal. Calcd for $C_6H_6F_6O_3$ (**4**, R = OCH_3): C, 43.91; H, 3.69; F, 23.15. Found: C, 44.01; H, 3.72; F, 22.36. Found (**5**): C, 39.40; H, 2.01

3-Phenyl-2,4,4-trifluorocyclobut-2-en-1-one (6, R = F). A solution of 0.1 mol of **2** (R = F) in 50 ml of SO_2 at −40 to −45 °C was treated dropwise with 10 g (0.13 mol) of benzene. After addition was about two-thirds completed, a yellow-orange precipitate formed. After complete addition, the SO_2 was evaporated to give a dark solid, which was hydrolyzed by stirring with 150 ml of water. The resultant red-orange organic layer was taken up in methylene dichloride, dried ($MgSO_4$), and distilled to give 13.2 g (67%) of **6** (R = F): bp 56 °C (0.4 mm); mp 36.5-37.5 °C; ir (mull) 1806 (C=O), 1650 (cyclobutene C=C), 1595 cm^{-1} (aromatic C=C); NMR (CCl_4) ^1H δ 7.60 (m), ^{19}F ϕ −101.2 (t, 1, J = 23.1 Hz), −113.0 (d, 2, J = 23.1 Hz).

Anal. Calcd for $C_{10}H_5F_3O$: C, 60.62; H, 2.54; F, 28.76. Found: C, 60.81; H, 2.61; F, 28.69.

2-Chloro-3-phenyl-4,4-difluorocyclobut-2-en-1-one (6, R = Cl). Benzene (10 g, 0.13 mol) was added dropwise to 0.1 mol of **2** (R = Cl) in 50 ml of SO_2 at −40 to −45 °C. The solution immediately turned yellow orange. After complete addition, the solution was warmed to −10 °C for 30 min, then was rechilled to −40 to −50 °C, and finally was carefully quenched in 250 ml of ice water. After complete hydrolysis, the pale yellow organic layer was dissolved in methylene dichloride, dried ($MgSO_4$), and the solvent distilled off. The residual oil crystallized to give 16.5 g (77%) of crude product which was recrystallized from hexane to afford pure **6** (R = Cl): mp 77.5–78 °C; ir (mull) 1805 (C=O), 1597, 1590, 1572 cm^{-1} (C=C); NMR (CCl_4) ^1H δ 7.5–8.1 (m), ^{19}F ϕ −110.5 (s).

Anal. Calcd for $C_{10}H_5ClF_2O$: C, 55.97; H, 2.35; F, 17.71. Found: C, 56.23; H, 2.44; F, 17.64.

References and Notes

(1) (a) N. C. Deno, *Carbonium Ions*, **2**, 783 (1970); (b) G. A. Olah et al., *J. Am. Chem. Soc.*, **97**, 5489 (1975) and references cited therein.

(2) R. West and P. T. Kwitkowski, *J. Am. Chem. Soc.*, **88**, 5280 (1966).

(3) G. A. Olah and Y. K. Mo, *Adv. Fluorine Chem.*, 7, 109 (1973).

(4) R. D. Chambers, R. S. Matthews, and A. Parkin, *J. Chem. Soc., Chem. Commun.*, 509 (1973).

(5) The NMR line shapes were calculated at various temperatures and exchange rates using a program written by P. Meakin et al. (P. Meakin, E. L. Muetterties, F. N. Tebbe, and J. P. Jesson, *J. Am. Chem. Soc.*, **93**, 4701 (1971)) on a Univac 1108 computer and plotted on Calcomp plotter. The system was treated as a two-site problem with first-order couplings with fluorine atoms and appropriate population ratios and relaxation times.

(6) D. C. F. Law, S. W. Tobey, and R. West, *J. Org. Chem.*, **38**, 768 (1973).

(7) An independent synthesis of perfluorocyclobutenone will be reported in a forthcoming paper (B. E. Smart and C. G. Krespan).

(8) Methoxy-group rotational barriers in neutral systems are typically low, e.g., 2.7 kcal/mol in dimethyl ether (J. G. Astin in "Determination of Organic Structures by Physical Methods", Vol. I, E. A. Braude and F. C. Nachod, Ed., Academic Press, New York, N.Y., 1955, p 525). Although barriers to rotation about the carbonyl carbon–oxygen bond in methylated or protonated aldehydes and ketones are not experimentally known, calculated barriers for the protonated carbonyl species range from a minimum value of 17 kcal/mol (D. M. Brouwer, *Recl. Trav. Chim. Pays-Bas*, **86**, 879 (1967)) to 25–30 kcal/mol (P. Roos, *J. Chem. Phys.*, **49**, 4902 (1968)).

(9) For a discussion of puckered homoaromatic cyclobutenyl cations, see ref 1b.

(10) J. T. Barr et al., *J. Am. Chem. Soc.*, **72**, 4480 (1950).

(11) J. D. Park, C. M. Snow, and J. R. Lacher, *J. Am. Chem. Soc.*, **73**, 2342 (1951).

(12) J. D. Park, S. M. Sharrah, and J. R. Lacher, *J. Am. Chem. Soc.*, 71, 2337 (1949).

Participation of the Styrene Group as a Terminator of Biomimetic Polyene Cyclizations.[1] Formation of the *trans*-8-Methylhydrindan Ring System

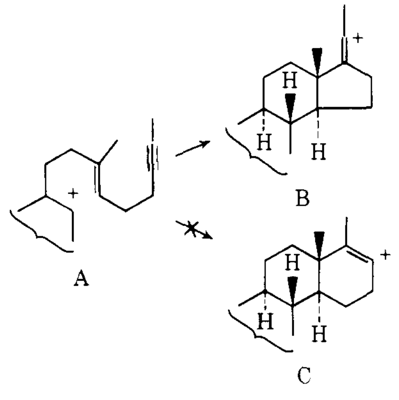
William S. Johnson* and Leonard A. Bunes[2]

Contribution from the Department of Chemistry, Stanford University, Stanford, California 94305.

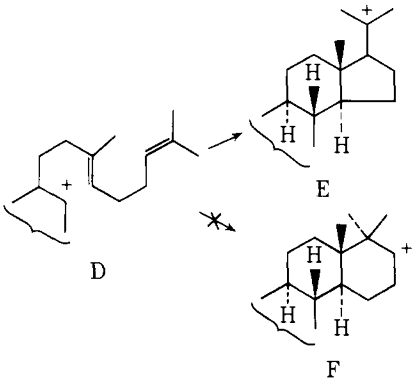
Received February 20, 1976

Abstract: The aim of this study was to examine the styrene group as a cyclization terminator of a biomimetic polyene cyclization, in the hope that it would participate so as to favor formation of a five-membered ring as suggested by the conversion of cation G into H. The model substrate **1** was synthesized from the bromodiene **6** (prepared according to Scheme I) by the sequence outlined in Scheme II. On treatment with stannic chloride in dichloromethane at −78 °C, substrate **1** underwent cyclization to give as the major product a hydrocarbon, presumably **11**, evidently produced from the initially formed benzylic cation by a series of 1,2-hydride and methyl shifts. Cyclization of **1** with trifluoroacetic acid, on the other hand, led to the bicyclic alcohol **12**. The structure and configuration of this product were established by degradation to the diol **18**, which was oxidized to the previously known dione **10**. Reduction of **10** with sodium borohydride gave the isomeric diol **19**, differing from **18** in the orientation of the hydroxyl at C-1.

Up to now the only generally successful method for the stereospecific production of five-membered rings via biomimetic polyene cyclizations has been through the participation of acetylenic bonds in the ring-closure process.[3] This result may be rationalized by postulating that a cation like A would prefer to cyclize so as to give a linear rather than a bent vinyl cation, i.e., B rather than C.



Systems with an appropriately placed isopropylidene terminating group (see cation D) have been shown also to give five- rather than six-membered rings, presumably because of a preference for forming the tertiary cation E over the six-membered ring secondary cation F. Such systems, however, have not yet been useful in synthesis because cations like E have a susceptibility to undergo backbone rearrangement.[4]



The present paper discloses the first phase of a study of the use of the styrene terminating group which, when incorporated in a molecule as suggested by partial formula G, was envisaged as likely to yield products derived from five-membered ring