Synthetic and Mechanistic Aspects of the Reaction of 1,1-Difluoro-2,2-bis(dimethylamino)ethene with Ethyl Propiolate

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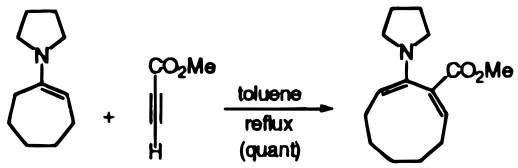
Received April 9, 1999

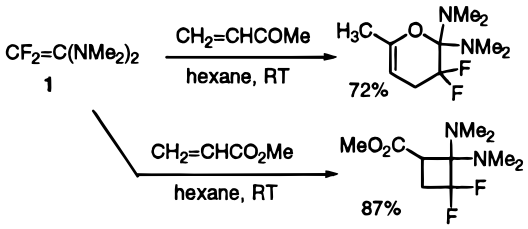
1,1-Difluoro-2,2-bis(dimethylamino)ethene undergoes a [2 + 2] cycloaddition with ethyl propiolate at −25 °C [$\Delta H^{\ddagger} = 4.2$ (±0.4) kcal/mol and $\Delta S^{\ddagger} = -56.7$ (±0.9) cal/mol·K], and the cyclobutene product undergoes electrocyclic ring opening at +15 °C [$\Delta H^{\ddagger} = 18.5$ (±0.6) kcal/mol and $\Delta S^{\ddagger} = -9.7$ (±1.0) cal/mol·K]. The resultant diene undergoes Diels−Alder reactions with electron-deficient dienophiles to give aromatic products. A complementary computational study addresses the issue of the [2 + 2] cycloaddition mechanism.

Cycloaddition reactions of enamines with electron-deficient alkynes are well documented.[1] In general, reactions of propiolates with enamines involve initial [2 + 2] cycloaddition reactions to form cyclobutene derivatives, with these cycloadducts undergoing a subsequent electrocyclic ring opening, quite often spontaneously. As is the case in the example given below, such electrocyclic reaction is often followed by a rapid 1,5-hydrogen shift to alleviate the strain of the originally formed *cis,trans*-diene.[2] In the case of alicyclic enamines, the net result



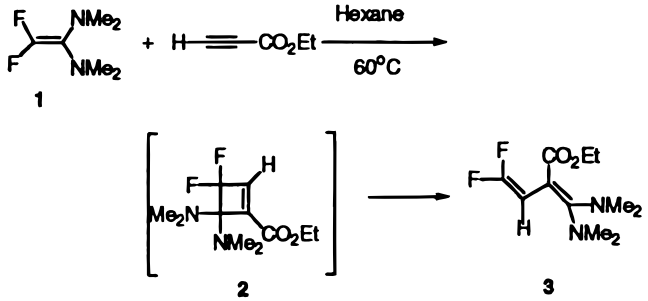
is a ring-enlarged product two carbon atoms larger than the original.[3] Such ring-enlargement processes have been successfully used in the synthesis of medium-sized heterocycles,[4] azulenes,[5] and natural products.[6] Similar two-carbon ring expansions can be carried out using silyl enol ethers, with Lewis acid catalysis.[7] Ketene acetals, *O,N*-acetals, and *N,N*-aminals undergo similar reactions with acetylenic esters.[8]

In the course of our comprehensive study of the chemistry of difluoroketene aminal **1**,[9] we have observed its [2 + 2] and [2 + 4] cycloadditions with electron-deficient alkenes.[9b] In this paper, we report the equally great reactivity of **1** with the electron-deficient alkyne, ethyl propiolate.



Results and Discussion

The reaction of aminal **1** with ethyl propiolate was carried out in hexane at 60 °C for 30 min to give diene **3** in 66% isolated yield. The formation of **3** occurs via a two-step process, the first being a [2 + 2] cycloaddition to form cyclobutene **2**, which is followed by its rapid ring-opening to form diene **3**.



During the course of the reaction at 60 °C, fluorine signals deriving from all three fluorinated species, **1**−**3**, were observed in the ^{19}F NMR spectrum of the reaction mixture. When the reaction was followed at room temperature by continuous monitoring of the ^{19}F NMR signals due to **1** (δ −113.45), **2** (δ −103.45), and **3** (δ −96.71 and −92.91 ppm), the concentrations were seen to vary as shown in Figure 1. The observed growth and disappearance of cyclobutene **2** is consistent with the sequence of reactions indicated above. Tracking the reaction at still lower temperatures, it was found that cyclobutene **2** is stable at temperatures below −15 °C.

(1) Cook, A. G. Cycloaddition Reactions of Enamines. In *Enamines: Synthesis, Structure, and Reactions*; Cook, A. G., Ed.; Basel: New York, 1987.

(2) Vos, G. J. M.; Benders, P. H.; Reinhoudt, D. N.; Egberink, R. J. M.; Harkema, S.; van Hummel, G. J. *J. Org. Chem.* **1986**, *51*, 2004−2011.

(3) Hesse, M. *Ring Enlargement in Organic Chemistry*; VCH: Weinheim, 1991.

(4) Acheson, R. M.; Elmore, N. F. *Adv. Heterocycl. Chem.* **1978**, *23*, 263−482.

(5) Hafner, K.; Kläs, H. C.; Böhm, M. C. *Tetrahedron Lett.* **1980**, *21*, 41−44.

(6) (a) Stork, G.; MacDonald, T. L. *J. Am. Chem. Soc.* **1975**, *97*, 1264−1265. (b) Becker, D.; Hughes, L. R.; Raphael, R. A. *J. Chem. Soc., Perkin Trans. 1* **1977**, 1674−1681.

(7) Clark, R. D.; Untch, K. G. *J. Org. Chem.* **1979**, *44*, 248−253.

(8) Brannock, K. C.; Burpitt, R. D.; Thweat, J. G. *J. Org. Chem.* **1962**, *28*, 1697−1698.

(9) (a) Xu, Y.; Dolbier, W. R., Jr. *J. Org. Chem.* **1997**, *62*, 1576−1577. (b) Xu, Y.; Dolbier, W. R., Jr. *J. Org. Chem.* **1997**, *62*, 6503−6506. (c) Xu, Y.; Dolbier, W. R., Jr. *Tetrahedron* **1998**, *54*, 6319−6328. (d) Xu, Y.; Dolbier, W. R., Jr. *Tetrahedron Lett.* **1998**, *39*, 9151−9154.

10.1021/jo990609m CCC: $18.00 © 1999 American Chemical Society
Published on Web 07/09/1999

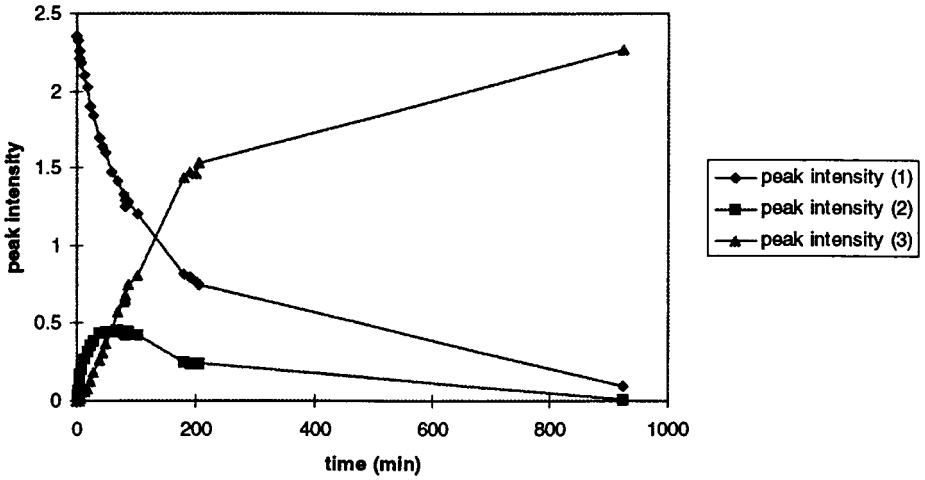


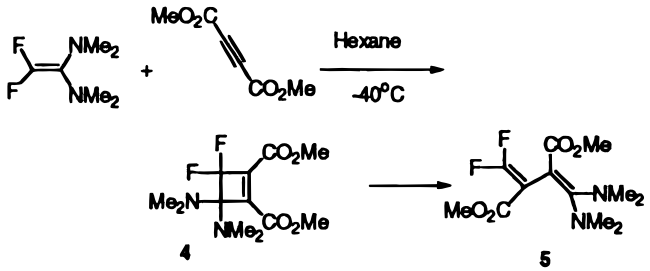
Figure 1. Concentration of **1**−**3** as a function of time in the reaction of **1** with ethyl propiolate in hexane at 20 °C

Table 1. Rate Constants for [2 + 2] Cycloaddition Reaction between 1 and Ethyl Propiolate in $CDCl_3$/Hexane (3:1)

T (°C)	$k/10^{-4}$ M^{-1} s^{-1}	T (°C)	$k/10^{-4}$ M^{-1} s^{-1}
−35	3.01 ± 0.25	−20	5.63 ± 0.01
−30	3.90 ± 0.11	−15	6.49 ± 0.01
−25	4.66 ± 0.03		

Consequently, it was possible to measure the rate constant of the cycloaddition reaction at such low temperatures and then to measure the rate constant of the isomerization of **2** → **3** at higher temperatures (vide infra).

The reaction of **1** with dimethyl acetylene dicarboxylate was also carried out. At room temperature, the reaction was complete in 10 min, but only an insoluble polymer product was obtained. When the reaction was carried out at −40 °C, a single product (singlet in the ^{19}F spectrum at δ −102.33 ppm) was detected. Cyclobutene **4** was



proposed as the structure of this product, but when the solution containing **4** was allowed to warm to room temperature, no diene **5** was able to be detected. Apparently, **5** undergoes immediate polymerization upon its formation, and attempts to isolate either **4** or **5** met with failure.

The [2 + 2] Cycloaddition Reaction. Measurement of the bimolecular rate constants of [2 + 2] cycloaddition of **1** with ethyl propiolate, in $CDCl_3$/hexane (3:1) at five temperatures (−35 to −15 °C), was carried out using variable-temperature NMR, the obtained rate constants being given in Table 1. From these rate constants, using the Eyring equation, activation parameters were obtained for the cycloaddition process: $\Delta H^{\ddagger} = 4.2$ (±0.4) kcal/mol and $\Delta S^{\ddagger} = -56.7$ (±0.9) cal/deg. This reaction is obviously largely entropy-controlled, and its huge observed negative activation entropy is reminiscent of those observed for ketene cycloadditions,[10] as well as those of [2 + 2] reactions proceeding via zwitterionic intermediates.[11] Mainly on the basis of product studies, concerted mechanisms have been proposed in some earlier reports of enamine−acetylenic ester cycloadditions.[12]

Rate constants were obtained in two different solvent mixtures at −20 °C [3:1 $CDCl_3$/hexane and toluene-d_8/hexane; 5.63 (±0.01) × 10^{-4} and 1.20 (±0.03) × 10^{-4} M^{-1} s^{-1}, respectively], giving a k_{rel} of 4.7. A solvent effect of this magnitude, with the small range of solvent polarity, unfortunately does not provide any definitive mechanistic insight. The kinetic results for this reactions can be considered consistent with either the highly ordered transition state of a concerted reaction or a mechanism involving a zwitterion intermediate, the large $\Delta S^{\ddagger}$ of which would derive partially from severe solvent constriction.[10a,11,13]

Computational Study. To gain additional mechanistic insight into the [2 + 2] reaction between ketene aminal **1** and ethyl propiolate, the reaction was examined computationally.

A single transition state involving concerted, but highly nonsynchronous, bond formation was located. In the gas phase, the standard enthalpy of activation for attaining this transition state ($\Delta H^{\ddagger}$) was calculated to be 13.6 kcal/mol, and the standard entropy of activation ($\Delta S^{\ddagger}$) was calculated to be −47.8 cal/mol·K. The reaction was found to be highly exothermic ($\Delta H° = -32.3$ kcal/mol.).

The structure of the transition state is depicted in Figure 2. In this transition state, the distance between C_{23} and C_2 where the C−C bond is forming, is 2.029 Å, and the distance between C_{24} and C_1 where the other C−C bond is forming, is 3.015 Å. Bond C_{23}−C_{24} is losing triple-bond character, its bond length changing from 1.186 to 1.228 Å. Bond C_{26}−C_{24} is developing some double-bond character, with its bond length changing from 1.441 to 1.389 Å (as compared to reactants).

An analysis of atomic charges (CHelpG) revealed that a substantial amount of charge is transferred (total 0.406

(10) (a) Huisgen, R.; Feiler, L. A.; Otto, P. *Chem. Ber.* **1969**, *102*, 3444−3459. (b) Brady, W. T.; O'Neal, H. R. *J. Org. Chem.* **1967**, *32*, 612−614.
(11) Huisgen, R. *Acc. Chem. Res.* **1977**, *10*, 117−124.
(12) Reinhoudt, D. N.; Verboom, W.; Visser, G. W.; Trompenaars, W. O.; Harkema, S.; Hummel, G. J. *J. Am. Chem. Soc.* **1984**, *106*, 1341−1350.
(13) Huisgen, R.; Otto, P. *J. Am. Chem. Soc.* **1968**, *90*, 5342−5343.

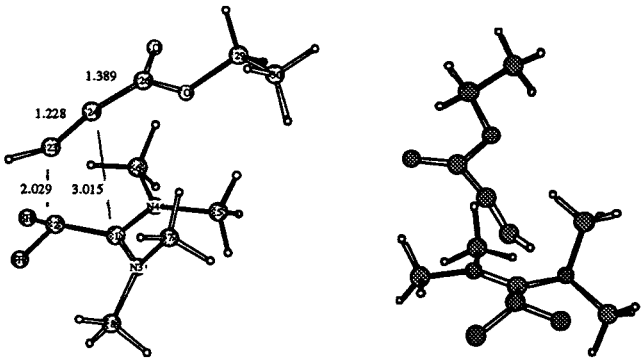


Figure 2. Structure of transition state (from two different views of points). Optimized at HF/3-21G(d) level of theory.

Table 2. Rate Constants for Electrocyclic Ring Opening of Cyclobutene 2 in $CDCl_3$/Hexane (3:1)

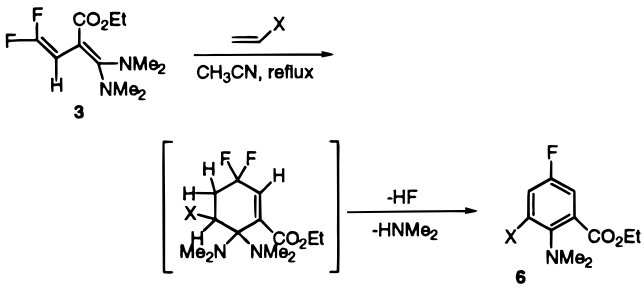
T (°C)	$k/10^{-4}$ s^{-1}	T (°C)	$k/10^{-4}$ s^{-1}
−5	0.41 ± 0.01	15	4.39 ± 0.09
5	1.34 ± 0.04	20	8.25 ± 0.16
10	2.41 ± 0.05	25	14.6 ± 0.2

e) from reactant **1** to reactant **2** in the transition state. Partial negative charges are developed mainly at C_{24} (−0.126e) and C_{26} (−0.141e). On the other side, partial positive charges are developed mainly at C_1 (+0.101e) and N_4 (+0.164e).

Although all of the computational data indicate that the reaction would be a concerted, nonsynchronous process with partial zwitterionic character in the gas phase, these results do not rule out the realistic possibility that under actual conditions of reaction in solution the reaction might well involve formation of a discrete zwitterionic *intermediate*.

Electrocyclic Ring-Opening Reaction. The rate constants for ring-opening of cyclobutene **2** were obtained at six temperatures (−5 to +25 °C) (Table 2), and the following activation parameters were obtained: $\Delta H^{\ddagger}$ = 18.5 (±0.6) kcal/mol and $\Delta S^{\ddagger}$ = −9.7 (±1.0) cal/mol·K. These activation parameters are consistent with the reaction proceeding via a normal, though obviously highly activated, electrocyclic ring-opening process. A much wider range of solvent conditions was examined for this reaction, with the rates ranging from 3.16 (±0.07) × 10^{-4} M^{-1} s^{-1} in 3:1 acetonitrile/hexane to 1.37 (±0.17) × 10^{-4} M^{-1} s^{-1} in 5:3 toluene-d_8/hexane, indicating little solvent effect for the reaction, a result consistent with the reaction's pericyclic nature.

Diels−Alder Chemistry of Diene 3. Recognizing that diene **3** might well play the role of diene in Diels−Alder reactions, it was allowed to react with various electron-deficient dienophiles in refluxing acetonitrile. No primary adducts were obtained. Instead, aromatic products, which were apparently formed via loss of HF and $HNMe_2$ from the presumed primary products, were isolated in fair to good yields. The proton and fluorine NMR spectra of the products indicate that **6a**−**d** are their probable structures. For example, **6a** exhibits two aromatic protons in the ^{1}H NMR at δ 7.28 and 7.39 ppm, each a doublet ($^3J_{HF}$ = 8.3 Hz, $^4J_{HH}$ = 3.1 Hz) and a triplet at δ −119.89 ppm in the ^{19}F NMR ($^3J_{HF}$ = 8.3 Hz), thus indicating that the two protons in **6a** are meta.



6a, X = CN (41%); **b**, X = CO_2Me (30%); **c**, R= COMe (39%); **d**, R=CHO (26%)

Conclusions

The unusually diverse reactive behavior of difluoroaminal **1** is further demonstrated by the kinetic and computational study of its [2 + 2] cycloaddition with ethyl propiolate. The resultant, thermally unstable cyclobutene product, **2**, undergoes electrocyclic ring opening below room temperature to produce diene **3**, which is observed to participate in Diels−Alder reactions with electron-deficient alkenes.

Experimental Section

1,1-Difluoro-4,4-bis(dimethylamino)-3-carbethoxy-1,3-butadiene (3). To a solution of 1,1-bis(dimethylamino)-2,2,2-trifluoroethane (1.7 g, 10 mmol) in hexane (10 mL) at 0°C under nitrogen was added *n*-BuLi (2.5 M in hexanes, 4.5 mL), after which the reaction mixture was allowed to warm to room temperature and stirred for 10 h. Then the reaction mixture (containing **1**) was distilled at reduced pressure into a 100 mL of dry ice/acetone-cooled receiving flask equipped with rubber septum, magnetic stir bar, and a water-cooled condenser. Before and after distillation, the total apparatus was maintained under a dry nitrogen atmosphere. Ethyl propiolate (0.72 g, 7.35 mmol) was added, and the reaction mixture was stirred for 30 min at 60 °C under dried nitrogen. The solvent was then distilled and the residue removed under reduced pressure to give **3** as a colorless liquid: 1.2 g (66%); bp 98−100 °C/0.9 mmHg; ^{1}H NMR δ 1.12 (t, J = 7.1 Hz, 3 H), 2.60−3.10 (m, 12H), 4.17 (q, J = 7.1 Hz, 2H), 5.45 (dd, J = 27.8, 3.7 Hz, 1H); ^{19}F NMR δ −96.71 (d, J = 48.4 Hz, 1F), −92.91 (dd, J = 50.9, 26.6 Hz, 1F); ^{13}C NMR δ 15.20, 40.36 (m), 58.47, 72.28, 80.29 (dd, J = 28.6, 16.0 Hz), 154.47 (dd, J = 287.4, 279.4 Hz), 166.49, 167.12; HRMS (EI) calcd for $C_{11}H_{18}F_2N_2O_2$ 248.1336, found 248.1313.

Ethyl 3-Cyano-2-(dimethylamino)-5-fluorobenzoate, 6a. In a 25 mL flask attached to a reflux condenser, compound **3** (0.34 g, 1.37 mmol) was mixed with acrylonitrile (0.1 g, in 5 mL of acetonitrile). The mixture was heated to reflux (became dark) and then stirred for 24 h under reflux. An ^{19}F NMR spectrum indicated that the starting material **3** was gone. H_2O (10 mL) was added, and the solution was extracted with diethyl ether (3 × 15 mL). The diethyl ether solutions were combined, washed with brine (2 × 10 mL), and dried with $MgSO_4$, and then the ether was removed by distillation. The residue was purified by column chromatography (hexane/ethyl acetate 10:1) to give a yellow oil: 0.13 g (41%); ^{1}H NMR δ 1.33 (t, J = 7.2 Hz, 3H), 2.88 (s, 6H), 4.32 (q, J = 7.2 Hz, 2H), 7.28 (dd, J = 7.3, 3.1 Hz, 1H), 7.39 (dd, J = 8.1, 3.1 Hz,1H); ^{19}F NMR δ −119.89 (t, J = 7.3 Hz, 1F); ^{13}C NMR δ 14.18, 43.52, 61.98, 111.10 (d, J = 9.1 Hz), 116.98, 122.21 (d, J = 23.7 Hz), 123.17 (d, J = 24.5 Hz), 129.64 (d, J = 6.5 Hz), 152.01, 155.95 (d, J = 245.8 Hz), 165.83; HRMS (CI) calcd for $C_{12}H_{14}FN_2O_2$ (M + 1) 237.1039, found 237.1027.

***N,N*-Dimethyl 2-Carbomethoxy-6-carbethoxy-4-fluoroaniline, 6b.** The procedure was the same as above except methyl acrylate was used as reagent: yield, 30%; ^{1}H NMR δ 1.38 (t, J = 7.5 Hz, 3H), 2.78 (s, 6H), 3.90 (s, 3H), 4.36 (q, J = 7.5 Hz, 2H), 7.35 (d. J = 8.2 Hz, 2H); ^{19}F NMR δ −120.32 (t,

J = 7.3 Hz, 1F); ^{13}C NMR δ 14.17, 43.49, 52.48, 61.49, 119.42 (d, J = 4.6 Hz), 119.72 (d, J = 4.6 Hz), 131.00, 131.74, 147.37, 156.80 (d, J = 243.9 Hz), 166.92, 167.24; HRMS (EI) calcd for $C_{13}H_{16}FNO_4$ 269.1063, found 269.1023.

Ethyl 3-Acetyl-2-(dimethylamino)-5-fluorobenzoate, 6c. The procedure was the same as above except that methyl vinyl ketone was used as reagent: yield, 39%; ^{1}H NMR δ 1.34 (t, J = 7.14 Hz, 3H), 2.45 (s, 3H), 2.71 (s, 6H), 4.32 (q, J = 7.14 Hz, 2H), 7.08 (dd, J = 7.69, 3.02 Hz, 1H), 7.29 (dd, J = 8.24, 3.02 Hz, 1H); ^{19}F NMR δ −118.83 (t, J = 7.27 Hz, 1F); ^{13}C NMR δ 14.23, 29.44, 43.60, 61.75, 117.81 (d, J = 22.9 Hz), 119.29 (d, J = 24.1 Hz), 130.97, 142.11, 146.28, 157.79 (d, J = 246.2 Hz), 166.93, 202.72; HRMS (M + 1) calcd for $C_{13}H_{16}FNO_3$ 253.1114, found 253.1073.

Ethyl 2-(Dimethylamino)-5-fluoro-3-formylbenzoate, 6d. The procedure was the same as above except that acrolein was used as reagent: yield, 26%; ^{1}H NMR δ 1.42 (t, J = 7.2 Hz, 3H), 2.92 (s, 6H), 4.40 (q, J = 7.2 Hz, 2H), 7.49 (dd, J = 8.1, 3.2 Hz, 1H), 7.57 (dd, J = 8.1, 3.2 Hz, 1H), 10.32 (d, J = 3.1 Hz, 1H); ^{19}F NMR δ −118.17 (t, 7.27 Hz, 1F); ^{13}C NMR δ 14.21, 44.99, 61.92, 117.74 (d, J = 22.7 Hz), 122.85 (d, J = 24.7 Hz), 131.49 (d, J = 6.6 Hz), 134.60 (d, J = 6.1 Hz), 151.42, 157.96 (d, J = 246.3 Hz), 166.65, 191.05; HRMS (EI) calcd for $C_{12}H_{14}FNO_3$ 239.0958, found 239.0915.

Procedures for Obtaining Kinetic Data. Cycloaddition Reaction of 1 with Ethyl Propioate. The kinetic experiments were run at five different temperatures in 3:1 deuterated chloroform/hexane, −15, −20, −25, −30, and −35 °C, and 3:1 deuterated toluene/hexane at −20 °C. The peak intensity of difluoroketene aminal **1** was recorded relative to the peak intensity of internal standard α,α,α-trifluorotoluene. In these experiments, an excess of ethyl propiolate (1.26 M) was used to ensure pseudo-first-order conditions.

A solution of ketene aminal **1** (0.2 mL in 0.6 mL of deuterated chloroform with ca. 7 mg of α,α,α-trifluorotoluene as an internal standard) was added to an NMR tube, which was cooled to −40 °C. Then 89.4 mg of ethyl propiolate was added. The reaction progress was monitored by ^{19}F NMR using variable NMR kinetics.

A first-order rate plot were made, plotting the logarithm of the relative peak decrease of **1** versus time. Straight lines were obtained, indicating a probable pseudo-first-order process, and the observed rate constant, k_{obs}, was obtained. The bimolecular rate constants were obtained using $k_{obsd} = k_{bimolec}$[ethyl propiolate] ([ethyl propiolate] = 1.26 M), and they are given in Table 1.

The enthalpy of activation, $\Delta H^{\ddagger}$, and entropy of activation, $\Delta S^{\ddagger}$, of the reaction were obtained from the Eyring equation, $k = (kT/h) \exp(-\Delta H^{\ddagger}/RT) \exp(\Delta S^{\ddagger}/R)$, where k is the Boltzmann constant (1.38×10^{-23} J K^{-1}) and h is Planck's constant (6.63×10^{-34} J s). A linear least-squares regression plot of $\ln(k/T)$ versus $1/T$ yields $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ from the slope and the intercept. Intercept = $\ln(k/h) + \Delta S^{\ddagger}$, slope = $-\Delta H^{\ddagger}/R$. So $\Delta H^{\ddagger}$ = 2094.1 × 1.987 Cal/mol = 4.2 kcal/mol, $\Delta S^{\ddagger}/R = -4.758 - \ln(k/h) =$ -4.758−23.77 = −28.52 K^{-1}, and $\Delta S^{\ddagger}$ = −56.7 cal/mol K.

Ring-Opening Isomerization of Ethyl 4,4-Bis(dimethylamino)-3,3-difluorocyclobutenecarboxylate, 2. The kinetic experiments were run at different solvents at 10 °C and run at six different temperatures in 3:1 deuterated chloroform/hexane. The peak intensity of **2** was recorded relative to the peak intensity of internal standard, α,α,α-trifluorotoluene.

First-order rate plots of the data were made, plotting the logarithm of the relative peak decrease against time. Straight lines were obtained, indicating a first-order process, and an observed rate constant was obtained from the slope.

Computational Methods. All the calculations were performed using the Gaussian 94W program package.[14] Reactants, product, and transition structure were optimized at the restricted Hartree−Fock (HF)[15] level of theory using the 3-21G-(d) basis set.[16] Frequency calculations were performed at the same level of theory to identify the saddle point and minima and also to obtain zero-point energies (scaled by 0.9409). Single-point energies were computed at the restricted Becke-style 3-parameter (B3LYP)[17] level of theory using the 6-31G-(d) basis set.[18] Atomic charge distributions were calculated using the CHelpG scheme.[19]

Acknowledgment. Support of this work in part by the National Science Foundation is acknowledged with thanks.

Supporting Information Available: ^{1}H, ^{13}C, and ^{19}F NMR spectra of **3** and **6a**−**d**; Tables of kinetic data. This material is available free of charge via the Internet at http://pubs.acs.org.

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(14) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; Montgomery, J. A., Jr.; Stratmann, R. E.; Burant, J. C.; Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B., Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Malick, D. K.; Rabuck, A. D., Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Gonzalez, C.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Andres, J. L.; Gonzalez, C.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. Gaussian, Inc., Pittsburgh, PA, 1995.

(15) Pople, J. A.; Nesbet, R. K.; *J. Chem. Phys.* **1954**, *22*, 571−572.

(16) (a) Binkley, J. S.; Pople, J. A.; Hehre, W. J. *J. Am. Chem. Soc.* **1980**, *102*, 939. (b) Gordon, M. S.; Binkley, J. S.; Pople, J. A.; Pietro, W. J.; Hehre, W. J. *J. Am. Chem. Soc.* **1982**, *104*, 2797. (c) Pietro, W. J.; Francl, M. M.; Hehre, W. J.; Defrees, D. J.; Pople, J. A.; Binkley, J. S. *J. Am. Chem. Soc.* **1982**, *104*, 5039. (d) Dobbs, K. D.; Hehre, W. J. *J. Comput. Chem.* **1986**, *7*, 359. (e) Dobbs, K. D.; Hehre, W. J. *J. Comput. Chem.* **1987**, *8*, 861. (f) Dobbs, K. D.; Hehre, W. J. *J. Comput. Chem.* **1987**, *8*, 880.

(17) Becke, A. D. *J. Chem. Phys.* **1993**, *98*, 5648−5652.

(18) Hariharan, P. C.; Pople, J. A. *Theor. Chim. Acta* **1973**, *28*, 213−222.

(19) Breneman, C. M.; Wiberg, K. B. *J. Comput. Chem.* **1990**, *11*, 361.