4-*Endo-Trig* Cyclization Processes Using Bis(collidine)bromine(I) Hexafluorophosphate as Reagent: Preparation of 2-Oxetanones, 2-Azetidinones, and Oxetanes

Fadi Homsi and Gérard Rousseau*

Laboratoire des Carbocycles (Associé au CNRS), Institut de Chimie Moléculaire d'Orsay, Bât. 420, Université de Paris-Sud, 91405 ORSAY, France

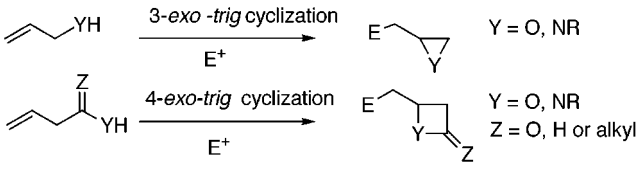
Received June 1, 1998

Reaction in methylene chloride of bis(collidine)bromine(I) hexafluorophosphate with α,β-unsaturated acids and α,β-unsaturated *N*-sulfonamides was found to lead diastereospecifically to the corresponding 2-oxetanones and 2-azetidinones in moderate yields (23−60%), by an almost unknown 4-*endo* cyclization. This process allow the synthesis of these interesting classes of products in one step from common substrates. Similarly, the reaction of cinnamic alcohols led, by the same cyclization procedure, to oxetanes (20−36%); the presence of a *gem*-dimethyl group in α of the alcohol function appeared beneficial.

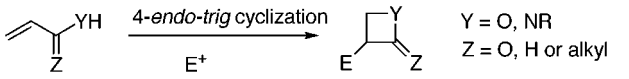
The preparation of small ring compounds by electrophilic cyclizations has mainly been reported for the preparation of epoxides and 2-oxetanones.[1] The obtention of epoxides by electrophilic addition of halogens on the carbon−carbon double bond of allylic alcohols was first published 60 years ago[2] and since then extensively studied.[3] The preparation of 2-oxetanones by cyclization of 3-butenoic acids was observed by Barnett in the 1970s[4] and then applied in organic synthesis.[3i,5] Likewise, since the initial report by Magnus,[6] the preparation of oxetanes by electrophilic cyclization of homoallylic alcohols was reported.[3i,7] While less studied, the formation of nitrogen heterocycles such as aziridines,[8] azetidines,[9] and β-lactames [10] were also published. All these electrophilic ring closures occur by *exo*-mode cyclizations and are, as noticed by Baldwin,[11] favored processes (Scheme 1).

Contrary to these well-known cyclizations, the formation of four-membered ring compounds by an *endo-trig* process (Scheme 2) is less common. Bartlett, 60 years ago, reported that reaction of bromine with the sodium salt of dimethylsuccinic acid led to an oxetanone.[12] Subsequently, similar results were obtained with cinnamic acid derivatives[13] and more recently with some α,β-unsaturated acids in the presence of calcium hypochlorite.[14] Formation of an oxetane by reaction of iodine with an allylic alcohol was also reported.[3e] These four-membered heterocycles were generally obtained with low yields. These results can be explained by the high strain in the transition state.

Scheme 1



Scheme 2



Reaction of α,β-Unsaturated Acids. As part of our research on the preparation of medium ring compounds,[15]

(1) (a) Dowle, M. D.; Davies, D. I. *Chem. Soc. Rev.* **1979**, 171. (b) Harding, K. E.; Tiner, T. H. In *Comprehensive Organic Synthesis*; Trost, B. M., Ed.; Pergamon Press: New York, 1991; Vol. 4, p 363.

(2) Straus, F.; Kühnel, R. *Chem. Ber.* **1933**, *66*, 1834.

(3) (a) Winstein, S.; Goodman, L. *J. Am. Chem. Soc.* **1954**, *76*, 4373. (b) Lindgren, B. O.; Svahn, C. M. *Acta Chem. Scand.* **1970**, *24*, 2699. (c) Kartashov, V. R.; Krom, E. N.; Bodrikov, I. V. *Zh. Org. Khim.* **1970**, *6*, 15. (d) Barelli, L.; Bellucci, G.; Berti, C.; Golfarini, M.; Marioni, F.; Scartoni, V. *Gazz. Chim. Ital.* **1974**, *104*, 107. (e) Diner, U. E.; Worsley, M.; Lown, J. W. *J. Chem. Soc. C* **1971**, 3131. (f) Ganem, B. *J. Am. Chem. Soc.* **1976**, *98*, 858. (g) Santelli, M.; Viala, J. *Tetrahedron Lett.* **1977**, 4397. (h) Midland, M. M.; Halterman, R. L. *J. Org. Chem.* **1981**, *46*, 1227. (i) Evans, R. D.; Magee, J. W.; Schauble, J. H. *Synthesis* **1988**, 862.

(4) (a) Barnett, W. E.; McKenna, J. C. *Tetrahedron Lett.* **1971**, 2595. (b) Barnett, W. E.; McKenna, J. C. *J. Chem. Soc., Chem. Commun.* **1971**, 551. (c) Barnett, W. E.; Sohn, W. E. *J. Chem. Soc., Chem. Commun.* **1972**, 472. (d) Barnett, W. E.; Sohn, W. H. *Tetrahedron Lett.* **1972**, 1777. (e) Barnett, W. E.; Needham, L. L. *J. Org. Chem.* **1975**, *40*, 2843.

(5) (a) Cambie, R. C.; Hayward, R. C.; Roberts, J. L.; Rutledge, P. S. *J. Chem. Soc., Perkin Trans 1* **1974**, 1864. (b) Holbert, G. W.; Weiss, L. B.; Ganem, B. *Tetrahedron Lett.* **1976**, 4435. (c) Nicolaou, K. C.; Lysenko, Z. *J. Am. Chem. Soc.* **1977**, *99*, 3185. (d) Cook, C. H.; Cho, Y. S.; Jew. S. S.; Suh, Y. G.; Kang, E. K. *Arch. Pharmacal. Res.* **1983**, *6*, 45. (e) Cambie, R. C.; Rutledge, P. S.; Somerville, R. F.; Woodgate, P. D. *Synthesis* **1988**, 1009. (f) Shibata, I.; Toyata, M.; Baba, A.; Matsuda, H. *J. Org. Chem.* **1990**, *55*, 2487. (g) Askani, R.; Keller, U. *Liebigs Ann. Chem.* **1988**, 61. (h) Sutherland, J. K.; Watkins, W. J.; Bailey, J. P.; Chapman, A. K.; Davies, G. M. *J. Chem. Soc., Chem. Commun.* **1989**, 1386. (i) Gore, V. G.; Narasimham, N. S. *Indian J. Chem., Sect. B.* **1991**, *30*, 241. (j) Black, T. H.; Huang, J. *Tetrahedron Lett.* **1993**, *34*, 1411. (k) Mead, K. T.; Park, M. *Tetrahedron Lett.* **1995**, *36*, 1205.

(6) Ehlinger, E.; Magnus, P. *J. Am. Chem. Soc.* **1980**, *102*, 5005.

(7) (a) Manabe, S.; Nishino, C. *Tetrahedron* **1986**, *42*, 3461. (b) Brown, W. L.; Fallis, A. G. *Can. J. Chem.* **1987**, *65*, 1828. (c) Arjona, O.; Fernandez de la Pradilla, R.; Plumet, J.; Viso, A. *Tetrahedron* **1989**, *42*, 4565. (d) Arjona, O.; Fernandez de la Pradilla, R.; Plumet, J.; Viso, A. *J. Org. Chem.* **1992**, *57*, 774. (e) Galatsis, P.; Parks, D. J. *Tetrahedron Lett.* **1994**, *37*, 6611. (f) Galatsis, P.; Millan, S. D.; Nechala, P.; Ferguson, G. *J. Org. Chem.* **1994**, *59*, 6643. (g) Jung, M. E.; Nichols, C. J. *Tetrahedron Lett.* **1996**, *37*, 7667.

(8) Kitagawa, O.; Suzuki, T.; Taguchi, T. *Tetrahedron Lett.* **1997**, *38*, 8371.

(9) (a) Corey, E. J.; Loh, T. P.; AchyuthaRao, S.; Daley, D. C.; Sarshar, S. *J. Org. Chem.* **1993**, *58*, 5600. (b) Berthe, B.; Duturquin, F.; Paulmier, C. *Tetrahedron Lett.* **1997**, *38*, 1393.

(10) (a) Biloski, A. J.; Wood, R. D.; Ganem, B. *J. Am. Chem. Soc.* **1982**, *104*, 3233. (b) Rajendra, G.; Miller, M. J. *Tetrahedron Lett.* **1985**, *26*, 5385. (c) Rajendra, G.; Miller, M. J. *J. Org. Chem.* **1987**, *52*, 4471. (d) Rajendra, G.; Miller, M. J. *Tetrahedron Lett.* **1987**, *28*, 6257. (e) Knapp, S.; Levorse, A. *J. Org. Chem.* **1988**, *53*, 4006.

(11) Baldwin, J. E. *J. Chem. Soc., Chem. Commun.* **1976**, 734.

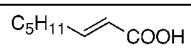
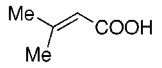
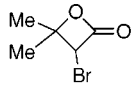
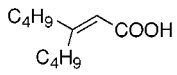
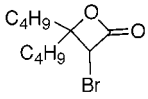
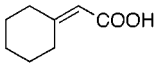
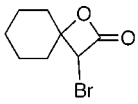
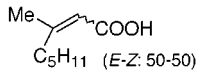
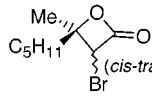
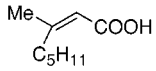
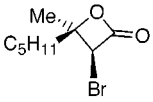
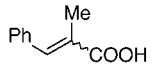
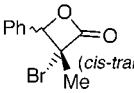
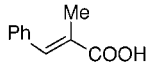
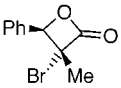
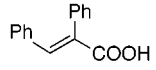
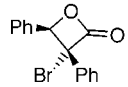
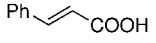
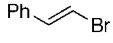
(12) Tarbell, D. S.; Bartlett, P. D. *J. Am. Chem. Soc.* **1937**, *59*, 408.

(13) (a) Price, C. C.; Blunt, H. W. *J. Org. Chem.* **1969**, *34*, 2484. (b) Kingsburry, C. A.; Max, G. *J. Org. Chem.* **1978**, *43*, 3131.

(14) Solas, D.; Wolinsky, J. *Synth. Commun.* **1981**, *11*, 609.

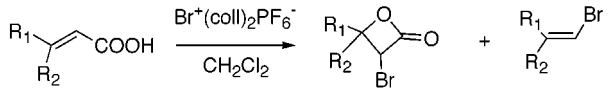
10.1021/jo9810361 CCC: $18.00
Published on Web 12/11/1998

Table 1. Reaction of α,β-Unsaturated Acids with Biscollidinebormine(I) Hexafluorophosphate

entry	acid **1**	product **2** (Yield, %)
a		polymer
b		 (23)
c		 (60)[a]
d		 (60)[a]
e	 (*E*-*Z*: 50-50)	 (60)[a] (*cis*-*trans*: 50-50)
f		 (60)[a]
g	 (*E*-*Z*: 50-50)	 (50)[a] (*cis*-*trans*: 50-50)
h		 (50)[a]
i		 (37)[a]
j		 (85)

[a] Also, 10% of the vinyl bromide formed by decarboxylation of the acid was isolated.

Scheme 3



1b-i **2b-i**

we were induced to study the reactivity of α,β-unsaturated acids with bis(collidine)bromine(I) hexafluorophosphate. The acids used were either commercially available or easily prepared by standard methods. After optimization, the reactions were carried out in methylene chloride, at room temperature, and in the presence of 1 equiv of collidine. Our results are reported Table 1. As our results show, the yields in β-lactones depend on the substitution at the β-position of the carbon−carbon double bond. With 2-octenoic acid (entry a), only polymeric materials were formed. With the β-dialkyl-substituted acids **1b**−**f**, the formation of 2-oxetanones and vinyl bromides were always observed in moderate yields (Scheme 3). Oxetan-2-ones **2b**−**i** were characterized from their ^{1}H and ^{13}C NMR and IR spectra; in particular, with IR, the ν_{CO} at 1840−1850 was always present. The vinyl bromides are all known products. The low yield observed with 3,3-dimethylacrylic acid, compared to the other β-dialkylacids was attributed to the volality of the product.

Cyclizations of (*Z*)-3-methylocten-2-oic acid **1f** and (*E*)-3-phenyl-2-methylpropenoic acid **1h** led only to one diastereoisomer (entries f and h), while the 50:50 *E*/*Z* mixture of these acids (entries e and g) led to a 50:50 mixture of diastereoisomers. These results show that the cyclizations are diastereospecific. The same result was obtained with acid **1i**, for which only one diastereoisomer was isolated. The *anti* addition of the bromine atom and the oxygen atom of the carboxylate on the carbon−carbon double bond conducts us to propose the structures indicated in Table 1. These results were confirmed in the case of the diastereoisomeric lactones **2g** in NMR by a NOESY experiment. Comportment of the β-phenyl propenoic acids **1g**−**j** appeared interesting; when these acids are substituted in α, we mainly observed the formation of oxetan-2-ones, while with cinnamic acid **1j**, only electrophilic decarboxylation was observed (evolution of carbon dioxide was observed as soon as the reagent was added). This decarboxylation reaction was also diastereospecific since *E*-bromostyrene (*E*/*Z* ≥ 98:2) was obtained quatitatively.

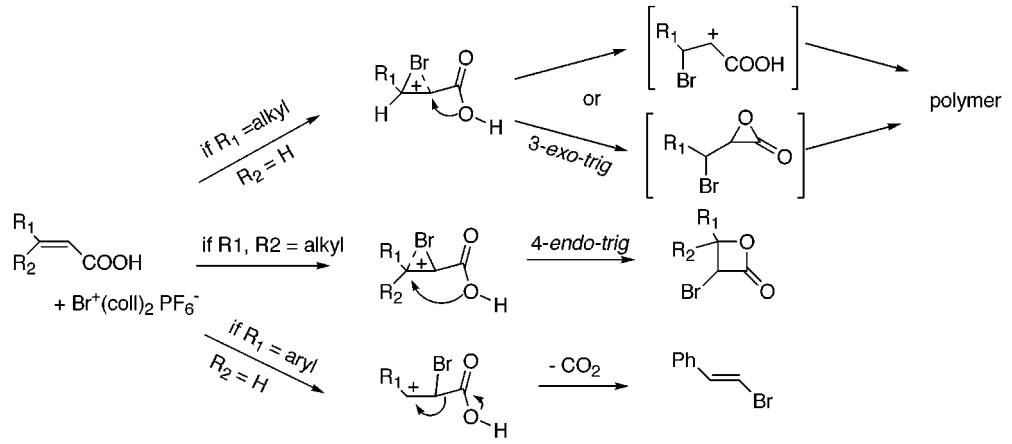
These results can be explained by the formation of an intermediate bromonium, which can follow different pathways depending of the degree of stabilization of the positive charge developed on the carbon β to the acid function (Scheme 4). When one alkyl group is present, the stabilization is insufficient to allow the formation of the β-lactone; the polymers observed could result from either the evolution of an instable α-lactone[16] (obtained by a favored 3-*exo*-*trig*-mode cyclization) or the evolution of an ionic intermediate.[13b] With two alkyl groups in β of the acid function, the stabilization of the charge appears enough to allow the 4-*endo*-mode cyclization. With cinnamic acid **1j**, the positive charge developed on C_3 weakened the C_1−C_2 bond and conducted to a carbon dioxide elimination. Similar electrophilic decarboxylations with cinnamic acid derivatives have been reported.[17] Surprisingly, chloronium addition on the carbon−carbon double bond of cinnamic acid did not lead to the chlorostyrene but instead to the oxetan-2-one in very low yield.[14] Finally, introduction of substituents at C_2 on the cinnamic framework diminished the positive charge on C_3, and the 4-*endo*-mode cyclization was again observed (entries g−i).

Examples of isomerization of β-lactones into γ-lactones are reported in the literature[4c−d,5a,c,f,j,18] (Scheme 5). So it is possible to wonder whether our 4-*endo*-lactones were not formed from the isomerization of the 3-*exo*-lactones. Some arguments can be advanced against this hypothesis. In the 4 → 5 ring enlargements known, the isomerization occurred slowly enough to be experimentally detected. In our case, this isomerization must have occurred with a very fast reaction rate since α-lactones are known to be highly instable compounds,[16] leading to polymers in solution even at very low temperature. The second argument is the generality of the 4-*endo* cylization, which was observed also for the formation of β-lactams and oxetanes (vide infra), for which this ring expansion seems unlikely.

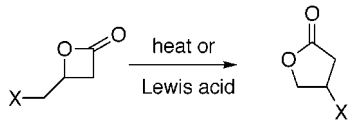
Reaction of α,β-Unsaturated Amides. The encouraging results obtained with the α,β-unsaturated acids led us to study the cyclization of α,β-unsaturated amides. Since no cyclization was observed with 3-methylbut-2-

(15) Homsi, F.; Rousseau, G. *J. Org. Chem.* **1998**, *63*, 5255.
(16) Wierlacher, S.; Sander, W.; Liu, M. T. H. *J. Org. Chem.* **1992**, *57*, 1051 and references therein.
(17) (a) Graven, A.; Jorgensen, K. A.; Dahl, S.; Stanczak, A. *J. Org. Chem.* **1994**, *59*, 3543. (b) Naskar, D.; Chowdhury, S.; Roy, S. *Tetrahedron Lett.* **1998**, *39*, 699.
(18) Black, T. H.; McDermott, T. S. *J. Chem. Soc., Chem. Commun.* **1991**, 184.

Scheme 4



Scheme 5



Scheme 6

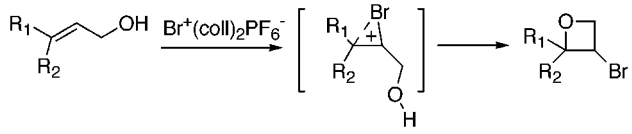
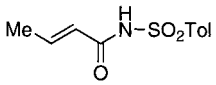
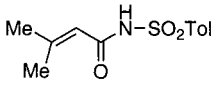
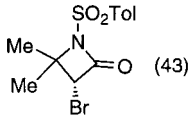
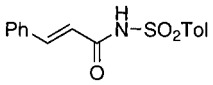
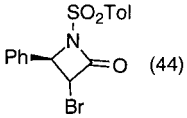
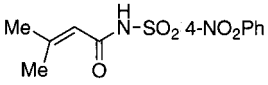
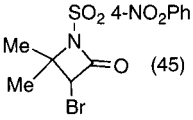
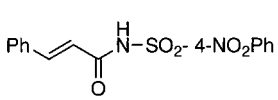
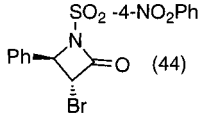


Table 2. Reaction of α,β-Unsaturated Amides with Biscollidinebromine(I) Hexafluorophosphate

entry	amide **3**	product **4** (Yield, %)
a		polymer
b		 (43)
c		 (44)
d		 (45)
e		 (44)

enoic acid amide, we decided to introduced a *p*-substituted phenylsulfonic group on the nitrogen to increase its acidity. The desired amides were prepared by reaction of the acid chlorides with the corresponding sulfonamines (25−50%). The modest yields are due to the low reactivity of the sulfonamines. The cyclization reactions were carried out in methylene chloride at room temperature in the presence of 1.3 equiv of bis(collidine)bromine(I) hexafluorophosphate. Our results are reported in Table 2.

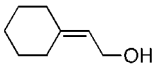
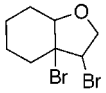
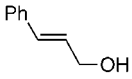
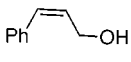
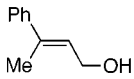
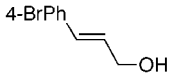
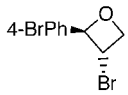
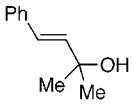
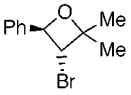
The *β*-lactams were characterized by ^{1}H and ^{13}C NMR and IR spectroscopy. No defined product was observed with the amide **3a**. Monosubtituted amides **3c** and **3e** led to only one diastereoisomer in which the two hydrogens were postulated to be *trans* on the basis of an *anti* addition of the bromine and nitrogen atoms on the carbon−carbon double bond. The ^{1}H NMR coupling constant for H_3-H_4 (1.5 Hz) appears compatible with this assumption.[19] Satisfactory yields were also obtained for the 3,3-dimethylacrylic amides **3b** and **3d**. Again, we can explain the formation of these *β*-lactams by a diastereospecific 4-*endo* cyclization. These results are important since they can allow a faster and easier synthesis of substiuted *β*-lactams, which are known to be useful compounds with potential applications as *β*-lactamases or inhibitors of 3-hydroxy-3-methyl glutarate coenzyme A synthase, human leukocyte elastase, poliovirus, and human rhinovirus C3-proteinase.[20]

Reaction of Allylic Alcohols. The reaction of allylic alcohols with bis(collidine)iodine(I) perchlorate has been reported to lead to epoxide or dioxanes.[3i] Similar results were obtained with bis(collidine)bromine(I) hexafluorophosphate.[21] To observe formation of oxetanes by electrophilic cyclization of allylic alcohols it appeared necessary to introduce substituents in the position *γ* to the alcohol function, which can stabilized the charge developed during the bromonium addition (Scheme 6). Our results are reported in Table 3.

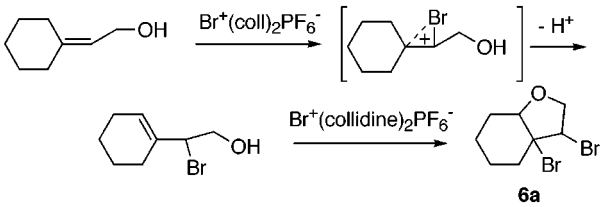
The alcohols studied were either commercially available or prepared by reduction from the corresponding α,*β*-unsaturated esters. The products were characterized from their spectroscopic data. The low yields observed for these cyclizations were due to the formation of tar materials and unidentified products. Only the alcohols substituted by an aryl group in the *β* position led to the oxetanes. With cyclohexylidene ethanol (entry a), the electronic effect of the cyclohexane ring appeared enough to stabilize the charge; however, the 4-*endo* product was not isolated due to an easy in situ formation of homoallylic alcohol, which after a second addition of bis(collidine)bromine(I) hexafluorophosphate, led to product **6a** of unknown stereochemistry (Scheme 7).

(19) (a) Nelson, O. A. *J. Org. Chem.* **1972**, *37*, 1447. (b) Casadei, M. A.; Inesi, A.; Moracci, F. M.; Occhialini, D. *Tetrahedron* **1989**, *45*, 6885.
(20) (a) Firestone, R. A.; Barker, P. L.; Pisano, J. M.; Ashe, B. M.; Dahlgren, M. E. *Tetrahedron* **1990**, *46*, 2255. (b) Skiles, J. W.; McNeil, D. *Tetrahedron Lett.* **1990**, *31*, 7277. (c) Thompson, K. L.; Chang, M. N.; Chiang, Y. C. P.; Yang, S. S.; Chabala, J. C.; Ariston, B. H.; Greenspan. M. D.; Hanf, D. P.; Yudkovitz, J. *Tetrahedron Lett.* **1991**, *32*, 3337. (d) Singh, R.; Cooper, R. D. G. *Tetrahedron* **1994**, *50*, 12049. (e) Han, W. T.; Trehan, A. K.; Wright, J. J. K.; Federici, M. E.; Seiler, S. M.; Meanwell, N. A. *Bioorg. Med. Chem.* **1995**, *3*, 1123.
(21) Rousseau, G. Unpublished results.

Table 3. Reaction of Allylic Alcohols with Biscollidinebromine(I) Hexafluorophosphate

entry	alcohol **5**	product **6** (Yield, %)
a		 (49)
b		 (36)
c		 (36)
d		 (25)
e		 (20)
f		 (67)

Scheme 7



Cinnamic alcohol led to *trans*-3-bromo-2-phenyloxetane. The stereochemistry was deduced from its ^{1}H NMR spectra. In particular, the coupling constant between H_2 and H_3 was found to be 6 Hz. This value appears to be characteristic of a *trans* coupling constant, since a higher value would be expected for a cis coupling constant.[22] The *cis* isomer of cinnamic alcohol led to the same oxetane. This result means that cyclizations of alcohols occur under thermodynamic control. The carbocationic character of the intermediate is probably more developed in this case than with the formations of oxetanones and azetidinones. This is the consequence of the less favored geometry for the cyclization of this kind of substrates compare to the cyclization of the acids and the amides. The presence of a *gem*-dimethyl group (entry f) was found to have a benefical influence since the yield in oxetane **6f** was notably increased compared with the yield obtained for the oxetane **6b**.

In conclusion, we have shown that the 4-*endo* cyclizations are possible and can be a convenient way to prepare 2-oxetanones, 2-azetidinones, and oxetanes in one step from linear substrates. The mechanism of these cyclizations is not as yet clear. Indeed, two possibilities can be considered: a direct cyclization from the intermediate bromonium or evolution of the bromonium to a carbocationic intermediate, followed by cyclization. The direct reaction of the bromonium intermediate, while sterically highly difficult, can be used to explain the results observed with the α,*β*-ethylenic acids and amides, since these reactions appeared diastereospecific. With allylic alcohols, the presence of a carbocationic intermediate is necessary to explain the results observed with the (*Z*)-cinnamic alcohol. These 4-*endo* cyclizations were not observed with bis(collidine)iodine(I) hexafluorophosphate (polymeric compounds were formed). We are not able at present to explain this difference in reactivity. Work is in progress to improve these highly unfavorable cyclizations with great potential in organic synthesis.

Experimental Section

General Remarks. All NMR spectra were measured in $CDCl_3$, and chemical shifts are expressed in ppm relative to internal $CHCl_3$. All solvents were purified by known standard procedures; in particular, methylene chloride was distilled from CaH_2. ^{1}H NMR spectra were measured in $CDCl_3$ at 200 or 250 MHz. The preparation of bis(collidine)bromine(I) hexafluorophosphate was previously reported.[15] 2-Octenoic acid, 3,3-dimethylacrylic acid, cinnamic acid, α-methylcinnamic acid, and α-phenylcinnamic acid are commercially available. Cyclohexylideneacetic acid, (*E,Z*)-3-methyl-2-octenoic acid, and 3-butyl-2-heptenoic acid were prepared in two steps by reaction of the corresponding ketone with methyl(triphenylphosphoranylidene)acetate followed by saponification of the ester function. Stereochemically pure methyl (*Z*)-3-butyl-2-heptenoate was obtained by preparative thin-layer chromatography (hexanes/ethyl acetate, 90:10). Its saponification led then to (*Z*)-3-butyl-2-heptenoic acid. The 50:50 mixture of (*E*/*Z*)-2-methyl-3-phenylacrylic acid was prepared by irradiation of (*E*)-2-methyl-3-phenylacrylic acid in benzene. The different acid chlorides were prepared by reaction of the different acids with oxalyl chloride. Allylic alcohols were commercially available or prepared by reduction of the corresponding esters.

3-Butyl-2-heptenoic Acid.[23] ^{1}H NMR: δ 0.85−0.95 (t, J = 6.0, 6H); 1.25−1.50 (m, 8H); 2.10−2.20 (t, J = 7.5 Hz, 2H); 2.55−2.65 (t, J = 7.5 Hz, 2H); 5.65 (s, 1H); 12.0−12.5 (m, 1H).

***(E)*-3-Methyl-2-octenoic Acid.**[24] ^{1}H NMR: δ 0.85−0.92 (t, J = 7 Hz, 3H); 1.20−1.50 (m, 6H); 2.15 (d, J = 1 Hz, 3H); 2.10−2.20 (t, J = 7 Hz); 5.7 (m, 1H); 12.0−12.5 (m, 1H).

***(Z)*-3-Methyl-2-octenoic Acid.**[25] ^{1}H NMR: δ 0.82−1.95 (t, J = 7 Hz); 1.20−1.55 (m, 6H); 1.90 (d, J = 1 Hz, 3H); 2.55−2.70 (t, J = 7 Hz, 2H); 5.68 (s, 1H); 12.0−12.5 (m, 1H).

General Procedure for the Preparation of Oxetan-2-ones. To bis(collidine)bromine(I) hexafluorophosphate (0.87 g, 1.87 mmol) in methylene chloride (20 mL), was added over a period of 15 min a solution of the acid **1** (1.4 mmol) and collidine (0.19 g, 1.6 mmol) in methylene chloride (10 mL). After 1h, silica gel was added (2 g) and the solvent was removed. The products were purified by flash chromatography (hexane/ethyl acetate, 90:10) to give the vinyl bromide and the oxetan-2-one **2**. The different results are reported Table 1.

3-Bromo-4,4-dimethyloxetan-2-one, 2b. ^{1}H NMR: δ 1.69 (s, 3H); 1.71 (s, 3H); 4.96 (s, 1H). ^{13}C NMR: δ 24.34; 26.18; 50.23; 81.42; 164.40. IR (neat): 1840 cm^{-1} (γ CO). Anal. Calcd for $C_5H_7O_2Br$: C, 33.55; H, 3.94. Found: C, 33.70; H, 4.03.

3-Bromo-4,4-dibutyloxetan-2-one, 2c. ^{1}H NMR: δ 0.85−1.00 (t, J = 6.0 Hz, 6H); 1.22−1.50 (m, 8H); 2.70−2.10 (m, 4H); 4.95 (s, 1H). ^{13}C NMR: δ 13.77; 13.81; 22.59 (2C); 25.46; 25.87; 33.91; 35.84; 49.45; 85.20; 165.10. IR (neat): 1840 cm^{-1} (γ CO). Anal. Calcd for $C_{11}H_{19}O_2Br$: C, 50.20; H, 7.28. Found: C, 50.27; H, 7.36.

3-Bromo-1-oxaspiro[3.5]nonan-2-one, 2d. ^{1}H NMR: δ 1.35−2.05 (m, 10H); 4.82 (s, 1H). ^{13}C NMR: δ 22.52; 22.90; 24.20; 33.06; 35.81; 49.67; 82.99; 165.03. IR (neat): 1840 cm^{-1} (γ CO). Anal. Calcd for $C_8H_{11}O_2Br$: C, 43.86; H, 5.06. Found: C, 43.77; H, 5.20.

(22) Balsamo, G.; Ceccarelli, G.; Crotti, P.; Macchia, F. *J. Org. Chem.* **1975**, *40*, 473.
(23) Normant, J. F.; Cahiez, G.; Chuit, C.; Villieras, J. *J. Organomet. Chem.* **1974**, *77*, 281.
(24) Ogura, K.; Nishino, T.; Koyama, T.; Seto, S. *J. Am. Chem. Soc.* **1970**, *92*, 6036.
(25) Sliwa, H.; Maitte, P. *Bull. Soc. Chim. Fr.* **1962**, 369.

3-Bromo-4-methyl-4-pentyloxetan-2-ones, 2e−f. From *(E)*-3-Methyl-2-octenoic acid. ^{1}H NMR: δ 0.85−0.92 (t, J = 7.5 Hz, 3H); 1.22−1.50 (m, 6H); 1.65 (s, 3H); 1.75−2.10 (m, 2H); 4.95 (s, 1H). ^{13}C NMR: δ 13.74; 23.28; 23.41; 23.70; 31.39; 39.08; 49.21; 83.63; 164.68. IR (neat): 1840 cm^{-1} (γ CO). From *(Z)*-3-Methyl-2-octenoic acid. ^{1}H NMR: δ 0.85−1.00 (t, J = 7.5 Hz, 3H); 1.25−1.50 (m, 6H); 1.68 (s, 3H); 1.86−2.00 (q, J = 10.0 Hz, 2H); 4.95 (s, 1H). ^{13}C NMR: δ 13.90; 22.38; 23.52 (2C); 31.63; 36.92; 50.58; 83.10; 164.80. IR (neat): 1840 cm^{-1} (γ CO). Anal. Calcd for $C_9H_{15}O_2Br$: C, 45.95; H, 6.43. Found: C, 45.79; H, 6.29.

3-Bromo-3-methyl-4-phenyloxetan-2-ones, 2g−h. From *(E)*-2-Methyl-3-phenylacrylic acid. ^{1}H NMR: δ 1.52 (s, 3H); 5.89 (s, 1H); 7.30−7.52 (m, 5H). ^{13}C NMR: δ 21.51; 60.35; 85.79; 125.26 (2C); 127.54 (2C); 129.45; 132.84; 167.52. IR (neat): 1855 cm^{-1} (γ CO). Anal. Calcd for $C_{10}H_9O_2Br$: C, 49.82; H, 3.76. Found: C, 49.71; H, 3.93. From *(Z)*-2-Methyl-3-phenylacrylic acid. ^{1}H NMR: δ 2.32 (s, 3H); 5.45 (s, 1H); 7.27−7.50 (m, 5H). ^{13}C NMR: δ 25.51; 56.26; 83.51; 125.74; 128.36; 128.94; 129.10; 129.70; 134.60; 167.62. IR (neat): 1840 cm^{-1} (γ CO).

3-Bromo-3,4-diphenyloxetan-2-one, 2i. ^{1}H NMR: δ 6.42 (s, 1H); 7.0−7.70 (m, 8H); 8.05 (dd, J = 8 and 1 Hz, 2H). ^{13}C NMR: δ 51.10; 88.51; 128.76 (2C); 128.98 (2C); 129.08 (5C); 191.00. IR (neat): 1850 cm^{-1} (γ CO). Anal. Calcd for $C_{15}H_{11}O_2Br$: C, 59.43; H, 3.66. Found: C, 59.56; H, 3.82.

Representative Procedure for the Preparation of Sulfonamides. A suspension of lithium toluenesulfonamide was prepared by dropwise addition of *n*-BuLi (1.25 M in hexane, 40 mL, 0.05 mol) to a solution of *p*-toluenesulfonamide (8.561 g, 0.05 mol) in THF (150 mL) at −78 °C. The cold bath was removed, and the heavy white suspension was allowed to warm to room temperature. After recooling to −78 °C, the suspension was transferred by cannulation to a solution of crotonyl chloride (0.025 mol, 2.6 g) in THF (10 mL) over a period of 20 min. The reaction mixture was left stirring for 24 h. Water (40 mL) was carefully added, and the THF was removed on the rotavap. The crude mixture was basified with 25% NaOH and extracted with ether (3 × 30 mL). The aqeous phase was acidified (pH 2) with aqueous HCl and extracted with ether (3 × 30 mL). The combined organic layers were dried over $MgSO_4$, and the ether was removed. The residue was dissolved in a minimum of ether, and after 48 h, the desired product crystallized out of the solution to give *N*-(but-2-enoyl)-4-methylbenzenesulfonamide, **3a**[26] (23%). White solid. mp 126−128 °C. ^{1}H NMR: δ 1.85 (dd, J = 7.5 and 1.0 Hz, 3H); 2.45 (s, 3H); 5.82 (d, J = 15.0 and 1.0 Hz, 1H); 6.85 (d, J = 15.0 and 1.0 Hz, 1H); 7.35 and 7.95 (d, J = 9.0 Hz, 4H); 8.95 (s, 1H). Anal. Calcd for $C_{11}H_{13}NO_3S$: C, 55.21; H, 5.48; N, 5.85. Found: C, 55.06; H, 5.46; N, 5.75.

***N*-(3-Methylbut-2-enoyl)-4-methylbenzenesulfonamide, 3b.** White solid. ^{1}H NMR: δ 1.93 (s, 3H); 2.20 (s, 3H); 2.45 (s, 3H); 4.90 (bs, 1H); 5.73 (s, 1H); 7.30 (d, J = 11.7 Hz, 2H); 7.80 (d, J = 11.7, 2H). Anal. Calcd for $C_{12}H_{15}NO_3S$: C, 56.90; H, 5.97; N, 5.53. Found: C, 56.82; H, 5.85; N, 5.45.

4-Methyl-*N*-(3-phenylacryloyl)benzenesulfonamide, 3c.[27] White solid. mp 137−138 °C. ^{1}H NMR: δ 2.45 (s, 3H); 6.42 (d, J = 18.7 Hz, 1H); 7.30−7.50 (m, 7H); 7.70 (d, J = 18.7 Hz, 1H); 8.05 (d, J = 12.5 Hz, 2H); 8.60 (s, 1H).

4-Nitro-*N*-(3-Methylbut-2-enoyl)benzenesulfonamide, 3d. White solid. ^{1}H NMR: δ 1.85 (s, 3H); 2.10 (s, 3H); 5.15 (bs, 1H); 5.55 (s, 1H); 8.15 (d, J = 9.0 Hz, 2H); 8.35 (d, J = 9.0 Hz, 2H). Anal. Calcd for $C_{11}H_{12}NO_5S$: C, 46.47; H, 4.25. Found: C, 46.52; H, 4.28.

4-Nitro-*N*-(3-phenylacryloyl)benzenesulfonamide, 3e. White solid. mp 130−134 °C. ^{1}H NMR: δ 5.10 (bs, 1H); 6.40 (d, J = 15 Hz, 1H); 7.30−7.50 and 8.25−8.40 (m, 9H); 7.70 (d, J = 15 Hz, 1H). Anal. Calcd for $C_{15}H_{12}NO_5S$: C, 54.21; H, 3.64. Found: C, 54.14; H, 3.74.

General Procedure for the Preparation of Azetidin-2-ones. To bis(collidine)bromine(I) hexafluorophosphate (0.75 g, 1.6 mmol) in methylene chloride (30 mL) was added a solution of the sulfonamide **3** (1.2 mmol) in methylene chloride (15 mL) by a push syringe over a period of 10 h. Subsequently, silica gel was added to the reaction mixture and the solvent was removed. The product was purified by flash chromatography (85:15, pentane/ethyl acetate). The different results are reported Table 2.

3-Bromo-4,4-dimethyl-1-(4-methylbenzenesulfonyl)-azetidin-2-one, 4b. White solid. mp 87−91 °C. ^{1}H NMR: δ 1.60 (s, 3H); 1.75 (s, 3H); 2.44 (s, 3H); 2.46 (s, 3H); 4.65 (s, 1H); 7.35 (d, J = 7.5 Hz, 2H); 7.90 (d, J = 7.5 Hz, 2H). ^{13}C NMR δ 21.67; 23.91; 26.01; 53.64; 67.67; 127.36 (2C); 130.02 (2C); 136.23; 145.61; 160.12. IR (neat): 1820 cm^{-1} (γ CO). Anal. Calcd for $C_{12}H_{14}BrNO_3S$: C, 43.39; H, 4.25; N, 4.25. Found: C, 42.98; H, 4.24; N, 3.85.

3-Bromo-1-(4-methylbenzenesulfonyl)-4-phenylazetidin-2-one, 4c. White solid. mp 125−129 °C. ^{1}H NMR: δ 2.45 (s, 3H); 4.60 (d, J = 1.25 Hz, 1H); 5.05 (d, J = 1.25 Hz, 1H); 7.20−7.40 (m, 7H); 7.65 (d, J = 8.1 Hz, 2H).^{13}C NMR: δ 21.66; 48.23; 67.83; 126.50 (2C); 127.54 (2C); 129.03 (2C); 129.71; 129.91 (2C); 133.91; 134.57; 145.79; 160.30. IR (neat): 1820 cm^{-1} (γ CO). Anal. Calcd for $C_{15}H_{13}BrNO_3S$: C, 50.54; H, 3.71; N, 3.68. Found: C, 50.28; H, 3.87; N, 3.51.

3-Bromo-4,4-dimethyl-1-(4-nitrobenzenesulfonyl)azetidin-2-one, 4d. White solid. mp 80−85 °C. ^{1}H NMR: δ 1.65 (s, 3H); 1.80 (s, 3H); 4.70 (s, 1H); 8.12 (d, J = 10 Hz, 2H); 8.45 (d, J = 10 Hz, 2H). ^{13}C NMR: δ 24.50; 25.65; 54.54; 69.52; 125.76 (2C); 129.77 (2C); 145.40; 152.13; 161.47. IR (neat): 1820 cm^{-1} (γ CO). Anal. Calcd for $C_{11}H_{11}BrN_2O_5S$: C, 36.38; H, 3.05; N, 7.71. Found: C, 36.29; H, 2.93; N, 7.84.

3-Bromo-1-(4-nitrobenzenesulfonyl)-4-phenylazetidin-2-one, 4e. White solid. mp 118−122 °C. ^{1}H NMR: δ 4.70 (d, J = 3.75 Hz, 1H); 5.15 (d, J = 3.75 Hz, 1H); 7.15−7.50 (m, 5H); 7.90 (d, J = 12.5 Hz, 2H); 8.30 (d, J = 12.5 Hz, 2H). 48.23; 67.80; 126.50 (2C); 127.55 (2C); 129.03 (2C); 129.91 (2C); 133.92; 134.60; 145.79; 152.13; 160.29. IR (neat): 1820 cm^{-1} (γ CO). Anal. Calcd for $C_{15}H_{10}BrN_2O_5S$: C, 43.92; H, 2.46; N, 6.83. Found: C, 44.12; H, 2.55; N, 6.94.

General Procedure for the Reaction of Allylic Alcohols. To bis(collidine)bromine(I) hexafluorophosphate (0.71 g, 1.5 mmol) in methylene chloride (30 mL) was added a solution of allylic alcohol (1.2 mmol) and collidine (0.15 g, 1.2 mmol) in methylene chloride (10 mL) over 6 h. Subsequently, silica gel (2 g) was added and the solvent was removed. The product was purified by flash chromatography over silica gel. The different results are reported Table 3.

3,3a-Dibromohexahydrobenzofuran, 6a. ^{1}H NMR: δ 1.40−2.10 (m, 8H); 3.95 (t, J = 8.0 Hz, 1H); 4.08 (bs, 1H); 4.30 (t, J = 8.0 Hz, 1H); 4.65 (t, J = 8.0 Hz, 1H). ^{13}C NMR: δ 19.15; 21.42; 24.65; 33.53; 57.72; 63.64; 71.40. Anal. Calcd for $C_8H_{12}Br_2O$: C, 33.84; H, 4.26. Found: C, 33.72; H, 4.51.

3-Bromo-2-phenyloxetane, 6b. ^{1}H NMR: δ 4.68 (q, J = 6 Hz, 1H); 4.95 (t, J = 6 Hz, 1H); 5.01(t, J = 6.0 Hz, 1H); 5.90 (d, J = 6 Hz, 1H); 7.30−7.60 (m, 5H). ^{13}C NMR: δ 43.19; 76.22; 91.99; 125.21 (2C); 128.66 (2C); 128.86; 139.40. Anal. Calcd for C_9H_9BrO: C, 50.73; H, 4.26. Found: C, 50.82; H, 4.42.

3-Bromo-2-methyl-4-phenyloxetane, 6d. ^{1}H NMR: δ 1.85 (s, 3H); 4.75 (m, 1H); 4.85−4.95 (m, 2H); 7.30−7.50 (m, 5H). ^{13}C NMR: δ 26.93; 48.83; 73.98; 90.35; 123.07; 126.27; 127.48; 128.46; 128.63; 128.75. Anal. Calcd for $C_{10}H_{11}BrO$: C, 52.89; H, 4.88. Found: C, 52.78; H, 4.68.

3-Bromo-2-(4-bromophenyl)oxetane, 6e. ^{1}H NMR: δ 4.65 (q, J = 6 Hz, 1H); 4.96 (qui, J = 6 Hz, 2H); 5.85 (d, J = 6 Hz, 1H); 7.34 (d, J = 8 Hz, 2H); 7.55 (d, J = 8 Hz, 2H). ^{13}C NMR: δ 42.86; 76.24; 91.23; 122.8; 126.80 (2C); 131.80 (2C); 138.4. Anal. Calcd for $C_9H_8Br_2O$: C, 37.02; H, 2.76. Found: C, 37.42; H, 2.11.

3-Bromo-2,2-dimethyl-4-phenyloxetane, 6f. ^{1}H NMR: δ 1.56 (s, 3H); 1.69 (s, 3H); 4.40 (d, J = 8 Hz, 1H); 5.60 (d, J = 8 Hz, 1H); 7.40−7.50 (m, 5H). ^{13}C NMR: δ 25.09; 29.00; 54.07; 84.37; 84.88; 125.24 (2C); 128.51 (2C); 128.57; 139.66. Anal. Calcd for $C_{11}H_{13}BrO$: C, 54.79; H, 5.43. Found: C, 54.85; H, 5.61.

JO9810361

(26) Niestroj, M.; Neumann, W. P.; Olaf, T. *Chem. Ber.* **1994**, *127*, 1131.

(27) Merck and Co, Inc. Br. Patent 902,881. *Chem. Abstr.* **1963**, *58*, 1410c.