VOLUME 118, NUMBER 1
JANUARY 10, 1996

JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

The Reaction of α-Diazo-β-hydroxy Esters with Boron Trifluoride Etherate: Generation and Rearrangement of Destabilized Vinyl Cations. A Detailed Experimental and Theoretical Study

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Received March 24, 1995. Revised Manuscript Received July 5, 1995[⊗]

Abstract: Cyclic ethyl 2-diazo-3-hydroxy carboxylates were prepared by treating ethyl diazoacetate with LDA followed by reaction with a series of cyclic ketones. Further treatment of these α-diazo-β-hydroxy esters with boron trifluoride etherate in various solvents affords an unusual array of products. Product types and ratios were found to be strongly dependent on ring size and the solvent used. The reaction proceeds by Lewis acid complexation of the alcohol functionality of the diazo hydroxy ester with BF_3 etherate followed by neighboring-group participation of the diazo moiety to generate a cycloalkylidene diazonium salt. Loss of nitrogen produces a highly reactive, destabilized, linear vinyl cation. Ring expansion *via* a 1,2-methylene shift leads to the formation of a more stable, bent cycloalkenyl vinyl cation. A subsequent 1,2-methylene shift results in ring contraction ultimately leading to a stable allylic cation. This cation is either trapped by the solvent or else undergoes cyclization with the adjacent ester group to give a lactone. Computational studies at the 6-31G* level were performed to determine the geometry of the optimized vinyl cations. Relative energies suggest a moderate energy gain for isomerization of the initial vinyl cation V_1 to the rearranged vinyl cation V_2 followed by a large stabilization in energy for subsequent conversion to the allyl cation A_1. Compared with isolated product distributions, the energy profiles suggest kinetically-controlled $V_1 \rightarrow V_2 \rightarrow A_1$ migrations. Finally, the calculations suggest that in diethyl ether the carbocations may be coordinated to a molecule of solvent resulting in "protected" cationic intermediates with nonlinear geometries.

Introduction

The chemistry of carbenium ions has been extensively studied since the turn of this century.[1−8] The major methods used for the generation of vinyl cations consist of (1) electrophilic addition to the triple bond of acetylenes[9] or the cumulene bond of allenes,[10] (2) intramolecular participation of acetylenic[11] and allenyl[12] bonds in solvolysis reactions, and (3) ionization of suitable vinylic derivatives.[2j,5,13] Less frequently employed methods include deamination,[14] fragmentation,[15] photolysis,[16]

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⊗ Abstract published in *Advance ACS Abstracts,* November 15, 1995.

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0002-7863/96/1518-0001$12.00/0

oxidative decarboxylation,[17] electrooxidation,[18] mass spectrometry,[19] and β-decay of a covalently-bonded tritium atom.[20] A necessary requirement for the direct solvolytic generation of vinyl cations is either the use of leaving groups of high nucleofugality, such as the trifluoromethanesulfonate (triflate) anion[21,22] or nonafluorobutanesulfonate (nonaflate) anion,[22,23] or the presence of stabilizing neighboring groups in the molecule.[2f,2g] If halide or tosylate leaving groups are employed in solvolysis reactions, electron-donating neighboring groups such as phenyl, vinyl, allyl, or cyclopropyl are necessary.

The solvolysis of cyclic vinyl substrates is of special interest because it can lead to a cyclic vinyl cation intermediate. The amount of strain inherent in the cyclic vinyl cation is a function of the ring size. Early studies in this area demonstrated the difficulty of forming vinyl cations with relatively small rings.[24] This difficulty was ascribed to the high energy of the transition state leading to the bent vinyl cation since larger, more flexible rings solvolyze at rates similar to or higher than those observed for the related acyclic *E*-2-butenyl sulfonates.[25] This observation suggests that vinyl cations prefer to adopt a linear geometry. Saturated carbocations where an electronegative substituent is attached directly to the carbon atom bearing the positive charge have been extensively studied.[26] In contrast, examples of "*destablized*" vinyl cations are rare but have been implicated as intermediates in the synthesis of β-functionalized alkynyl-(phenyl)iodonium salts.[27] Likewise, the photolysis of α-formyl and α-cyano vinyl halides affords products derived from the corresponding electronegatively-substituted vinyl cations.[28]

The sp-hybridized carbon atom of a vinyl cation possesses an empty π-orbital. As a result, atoms possessing nonbonding pairs of electrons, multiple bonds, and σ-bonds react rapidly with these reactive intermediates. For example, the solvolysis of vinyl derivatives in oxygen-containing solvents typically affords vinyl ethers and ketones as products which is the consequence of deprotonation of an intermediate oxonium ion.[29] Vinyl cations can also undergo reactions with the electrons of C−H and C−C σ-bonds. The deprotonation and rearrangement of vinyl cations to produce alkynes are examples of such σ-bond reactions. Rearrangement of these unsaturated cations can be classified into two general categories: (1) migration to the double bond with the formation of an allylic cation (**1** → **2**) and (2) migration of an alkyl group across the double bond whereby one vinyl cation is isomerized to another (**3** → **4**). These rearrangements generally occur when a more stable ion is formed from a less stable progenitor.

The aldol condensation of lithio-acyldiazomethanes **5** with aldehydes or ketones constitutes a facile method for the synthesis

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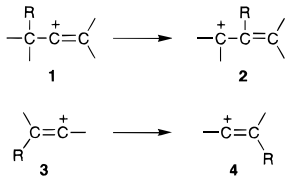
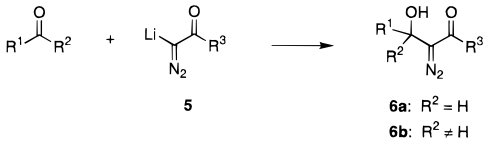
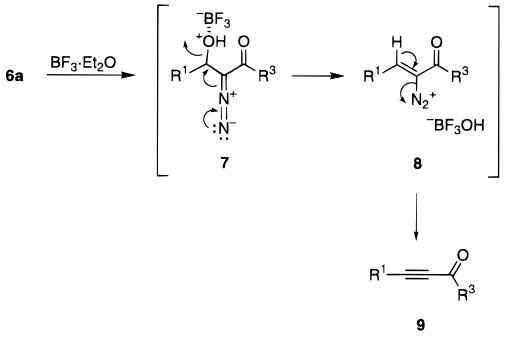


of α-diazo-β-hydroxycarbonyl compounds **6a,b**.[30−32] Earlier work in our groups as well as others have shown that these diazo compounds are valuable synthetic intermediates which undergo a wide range of transformations.[33−47] Notably, a recent study demonstrated that the reaction of α-diazo-β-hydroxy esters of type **6b** with BF_3·OEt_2 in various solvents affords an unusual array of products.[48] Since the mechanism associated with this process seemingly involves a vinyl cation intermediate, we decided to carry out a more in-depth investigation of the reaction of various α-diazo-β-hydroxy esters with BF_3·OEt_2 in order to gain a better understanding of the reaction pathway. Herein we detail the results of such a study.

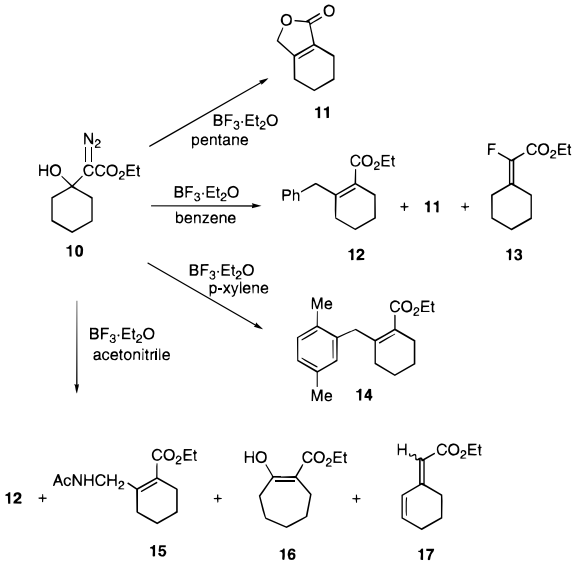


Results

The reaction of acyclic compounds of type **6a** (R^2 = H) with BF_3·OEt_2 in a polar solvent such as acetonitrile results in the formation of the corresponding acylacetylene **9** as the major product together with minor amounts of migration products.[31,38,43,44] The formation of **9** has been rationalized as proceeding *via* coordination of the diazoester with BF_3·OEt_2 followed by generation of the alkenyldiazonium salt **8**. Deprotonation of **8** with extrusion of molecular nitrogen affords alkyne **9**. The reaction of BF_3·OEt_2 with α-diazo-β-hydroxycarbonyl compounds derived from ketonic substrates **6b** became of interest to us, since the hydrogen atom located α to the diazo moiety, which is crucial in the conversion of **6a** to **9**, is missing with this set of compounds.



Cyclohexyl Derivatives. Our initial endeavors focused on the chemistry of the α-diazo ester **10** derived by treating cyclohexanone with ethyl lithiodiazoacetate. The outcome of the reaction of **10** with BF_3·OEt_2 in various solvents clearly indicates that the process is greatly influenced by the manner in which the reaction is performed. Thus, exposure of **10** to BF_3·OEt_2 in pentane resulted in the isolation of lactone **11** in 75% yield. Treatment of **10** in benzene provided **12** in 74% isolated yield along with minor amounts of lactone **11** as well



as 2-fluoroalkenoate **13**. The structure of **12** was confirmed by converting it into the previously reported *cis*-2-benzylcyclohexanecarboxylic acid.[49] Likewise, stirring a sample of **10** with BF_3·OEt_2 in *p*-xylene afforded **14** in 47% isolated yield. Finally, the reaction of **10** with BF_3·OEt_2 in acetonitrile resulted in the formation of 2-(acetamidomethyl)-1-cyclohexene carboxylate (**15**) as well as lactone **11** in 38% and 23% isolated yields, respectively. In this case, minor amounts of **16** and diene **17** were also obtained.

The possibility that these products are all derived from a common vinylogous α-diazo ester intermediate such as **20** was considered. Such an intermediate could conceivably be obtained by the dehydration of **10** followed by a precedented rearrangement of the initially-formed β,γ-unsaturated-α-diazo ester (**18**) to pyrazole **19.** Subsequent rearrangement of **19** under the reaction conditions could ultimately afford **20**. To test this hypothesis, α-diazo-β-hydroxy ester **10** was dehydrated using phosphorus oxychloride/pyridine to give vinyl diazo ester **18**.

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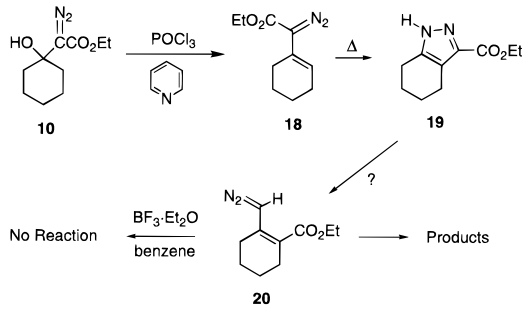
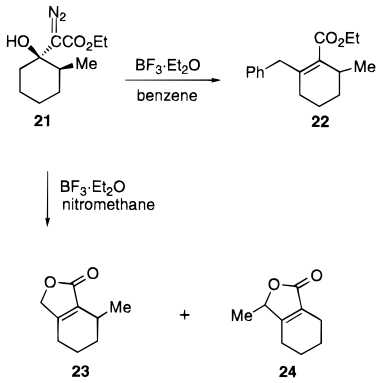
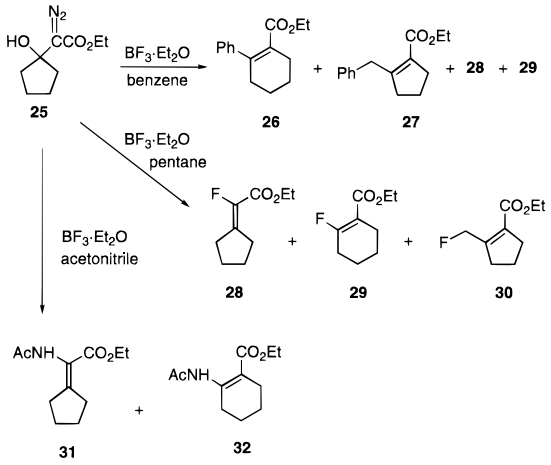
Heating **18** in *n*-octane at 110 °C provided ethyl 4,5-cyclohexa-1*H*-pyrazole-3-carboxylate (**19**) in 59% isolated yield. Exposure of **19** to $BF_3{\cdot}OEt_2$ in benzene, however, failed to give any detectable quantities of ethyl 2-benzyl-cyclohex-1-ene carboxylate (**12**), thereby ruling out this possibility.



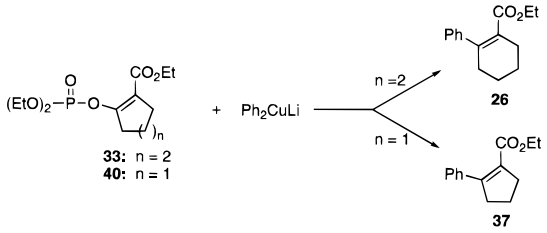
Reaction of the α-methyl substituted diazo alcohol **21** derived from 2-methylcyclohexanone with $BF_3{\cdot}OEt_2$ was next examined so as to probe the selectivity of the rearrangement. Treatment of **21** with $BF_3{\cdot}OEt_2$ in benzene afforded ethyl 2-benzyl-6-methylcyclohex-1-ene carboxylate (**22**) as the major product. When **21** was stirred with $BF_3{\cdot}OEt_2$ in nitromethane, a 1:1 mixture of methyl lactones **23** and **24** was isolated in 78% yield.



Cyclopentyl Derivatives. Exposure of ethyl 2-diazo-2-(1-hydroxycyclopentyl)acetate (**25**) to freshly-distilled $BF_3{\cdot}OEt_2$ in the presence of benzene afforded 2-phenylcyclohex-1-ene carboxylate (**26**) and 2-benzylcyclopent-1-enecarboxylate (**27**) as the major products. When the reaction was repeated using $BF_3{\cdot}OEt_2$ which had not been distilled, significant amounts of

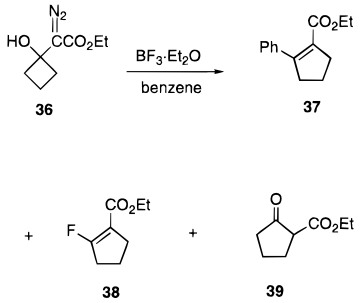


the fluorinated derivatives **28** and **29** were obtained in addition to **26** and **27** and is presumably due to the presence of some hydrogen flouride in the $BF_3{\cdot}OEt_2$. Compound **26** was independently synthesized by treating ethyl 2-(diethylphosphoryloxy)-1-cyclohexenecarboxylate (**33**)[50] with lithium diphenylcuprate.[51]

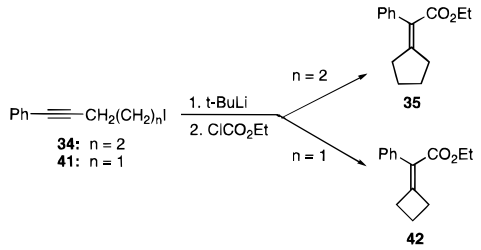


Interestingly, there were no signs of the unsaturated ester **35** in this reaction since we were able to prepare an independent sample from the *endo*-dig cyclization of the lithiate derived from iodide **34**[52] and subsequent trapping with ethyl chloroformate. When the reaction was carried out in pentane, ethyl α-fluorocyclopentylidene acetate (**28**), ethyl 2-fluoro-1-cyclohexene carboxylate (**29**), and ethyl 2-(fluoromethyl)-1-cyclopentene carboxylate (**30**) were obtained as the only products. In contrast to this finding, the reaction of **25** in acetonitrile afforded a 9:1 mixture of amides **31** and **32** as the sole products.

Cyclobutyl Derivatives. Treatment of the cyclobutyl analog (*i.e.*, **36**) with $BF_3{\cdot}OEt_2$ in benzene afforded ethyl 2-phenylcyclopent-1-ene carboxylate (**37**) (51%) and ethyl 2-oxocyclopentane carboxylate (**39**) (32%) as the major products accompanied by a small amount of ethyl 2-fluorocyclopent-1-ene carboxylate (**38**) (5%). An authentic sample of **37** was prepared



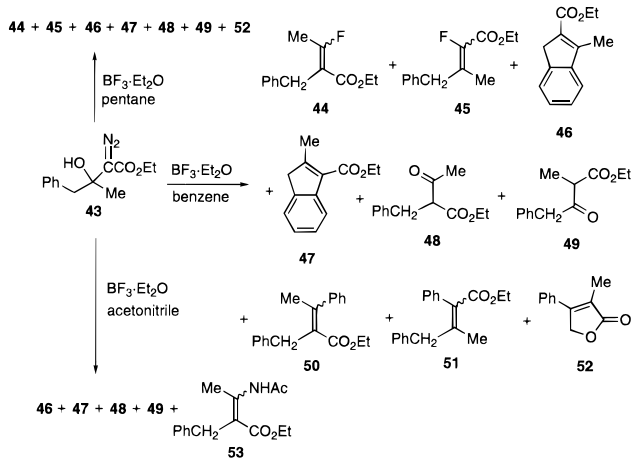
by treating ethyl 2-(diethylphosphoryloxy)-1-cyclopentene carboxylate (**40**)[50] with lithium diphenylcuprate.[51] There were no signs of the isomeric ester **42** in the crude reaction. An independently synthesized sample of **42** was prepared by the *endo*-dig cyclization of the lithiate derived from iodide **41**[52] followed by trapping with ethyl chloroformate.



Acyclic Derivatives. Intramolecular trapping of the cationic intermediates by a tethered phenyl group was also investigated. The reaction of diazo alcohol **43** with $BF_3{\cdot}OEt_2$ in benzene afforded a variety of products (*i.e.*, **44**−**52**) as a result of competitive trapping of the cationic intermediates by the solvent, fluoride ion, water, the ester functionality, and the π-system of

(50) Sum, F.-W.; Weiler, L. *Can. J. Chem.* **1979**, *57*, 1431.
(51) House, H. O.; Wilkins, J. M. *J. Org. Chem.* **1978**, *43*, 2443.
(52) Bailey, W. F.; Ovaska, T. V. *J. Am. Chem. Soc.* **1993**, *115*, 3080.

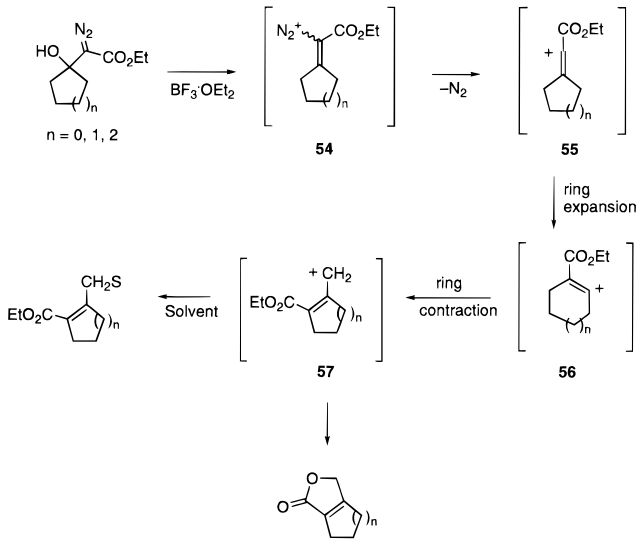
the pendant phenyl group. Indenes **46** and **47** arise by intramolecular trapping of a vinyl cation by the adjacent phenyl ring. Products **45** and **51** can be rationalized as being formed directly from the vinyldiazonium salt or *via* a destabilized vinyl cation intermediate (*vide infra*). The formation of compounds **44**, **46**, **48**, and **50** can be attributed to a 1,2-benzyl shift (*vide infra*) of the initially-formed vinyl cation and are found in larger amounts (*ca.* 80%). The remaining products (**49** and **52**) are derived from a 1,2-methyl shift of a destabilized vinyl cation intermediate (*vide infra*). When the reaction of **43** with BF_3·OEt_2 was repeated in pentane, the yield of indenyl products (**46** and **47**) was improved since competitive intermolecular capture by benzene is no longer possible. The outcome of the reaction of **43** with BF_3·OEt_2 in acetonitrile was markedly different. Specifically, the formation of the fluorinated products **44** and **45** was completely suppressed. Under these conditions, enamide **53** was obtained as the major product in good yield and lesser quantities of indenes **46** and **47** were also formed.



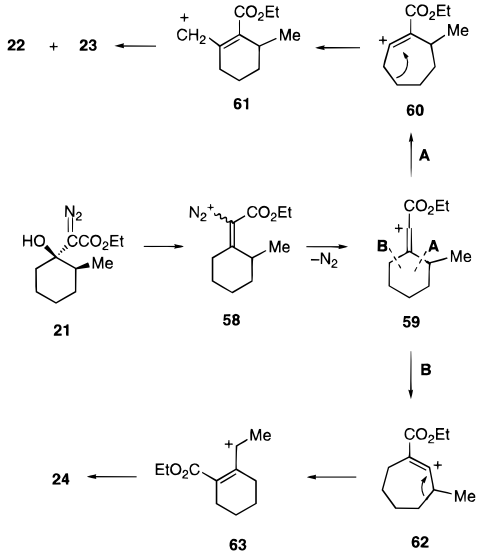
Unifying Mechanism: Carbocation Cascade. A mechanism which nicely accommodates the various products isolated with these α-diazo-β-hydroxy esters is outlined in Scheme 1. Complexation of the alcohol functionality of α-diazo-β-hydroxy ester **10** with a Lewis acid occurs first, and this is followed by generation of the cyclohexylidenediazonium salt. Loss of nitrogen produces a highly reactive, destabilized, linear vinyl cation **55**. Ring expansion *via* a 1,2-methylene shift results in the formation of a more stable, bent cycloheptenyl vinyl cation **56**. A subsequent 1,2-methylene shift resulting in ring contraction ultimately leads to the most stable allylic cation **57**. This cation is either trapped by the solvent or else undergoes cyclization with the adjacent ester group to give the observed lactone ring. Analogous mechanisms involving ring expansion of the initially-generated linear vinyl cation to the more stable bent vinyl cation followed by ring contraction to give an allylic cation are perfectly consistent with the products obtained in the reaction of α-diazo-β-hydroxy esters **21** and **25** with BF_3·OEt_2. The reaction of α-diazo-β-hydroxy ester **36** with BF_3·OEt_2 also appears to proceed via a ring expansion of the initially-generated linear vinyl cation to afford a more stable bent vinyl cation; however, a subsequent ring contraction apparently does not occur since no products arising from the intermediacy of an allylic cation are observed.

In the case of the 2-methylcyclohexanone system (**21**), ring expansion can occur by either of two pathways leading to the rearranged cycloheptenyl cation. The relative migratory aptitudes of the methylene bonds should determine which pathway is followed. The preferred migration (path A) corresponds to rearrangement of the more substituted methylene group which

Scheme 1



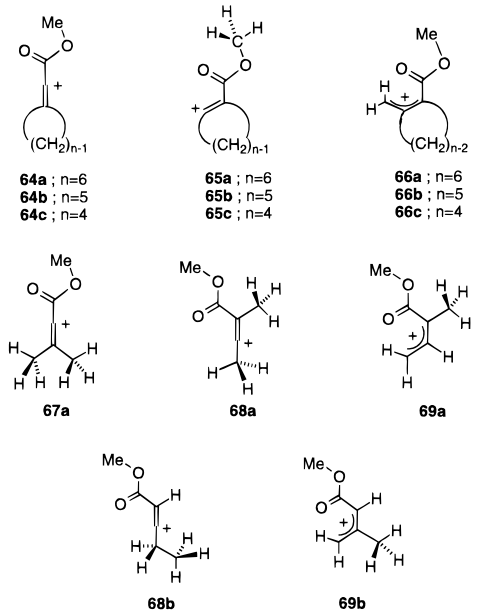
leads to allylic cation **61**. Bimolecular trapping of this primary allylic cation with benzene affords **22**, whereas intramolecular cyclization with the adjacent ester group leads to **23**. Capture of aromatic substrates by vinyl cations has been the subject of several studies.[2a] With nitromethane, some of the other lactone



(*i.e.*, **24**) derived by path B (intermediate **63**) is also formed. Likewise, the seemingly very complex reactions of the acyclic diazo alcohol **43** with BF_3·OEt_2 in various solvents can easily be accommodated by a mechanistic pathway similar to that observed with its cycloalkanone-derived counterpart.

Computational Considerations. The driving force for reactions proceeding through rearranging carbenium ions is generally thermodynamic: products being derived from the most stable cation(s). Qualitatively, this pattern is depicted in Scheme 1 by the transformation of destabilized vinyl cation **55** (V_1) to **56** (V_2) and onto the product-determining allyl cation **57** (A_1). To a first approximation, then, the transformation of various α-diazo-β-hydroxy esters might be expected to yield primarily A_1 products. As discussed below, this is not the case.

To explore the nuances of product distribution, we have performed 6-31G* ab initio optimizations for cyclic and acyclic intermediates **64**−**66** and **67**−**69**, respectively, as the methyl esters. The near linear geometries around $C{=}C^{+}{-}C$ for V_1 (171−172°; cf. Table 1 supporting information) are in accord



with many previous computational studies[2d] as well as the recently reported MP2/6-31G* and GIAO-MP2 structure for the cyclopropylcyclopropylidene-methyl cation.[53,54] Exceptionally expanded angles for the cyclic V_2's (147−168°) reflect a high degree of internal strain in the attempt to linearize.

Product Distributions. The 6-31G* relative energies for V_1, V_2, and A_1 (Table 1; supporting information) are in accord with expectation. A moderate energy gain for isomer V_2 compared to V_1 (−3 to −8 kcal/mol) is accompanied by a large stabilization for A_1 (−27 to −31 kcal/mol). The computational pattern applies to all systems under study and particularly favors the cyclobutane series. Based on cation stabilization alone, one would predict that products from the four- and five-membered ring precursors, **36** and **25**, respectively, would stem primarily from the corresonding allyl cations.

Quantitatively, product types and ratios are strongly dependent on ring size and solvent (Table 2). In benzene, for example, six-ring **10** delivers products derived primarily from allyl-cation **66a** (A_1) with less than 10% from the first formed vinyl cation **64a** (V_1). Cyclobutane **36** provides derivatives exclusively from the second vinyl cation **65c** (V_2). The five-membered ring **25** and acycle **43** yield a spread of products from all three intermediates V_1, V_2, and A_1. These results would not seem to be governed exclusively by ground state thermodynamics for cations stemming from different starting materials. Consequently, we have examined the barriers between intermediates.

The transition state between V_1 and V_2 unencumbered by cyclic constraints has been modeled by the fully optimized saddle point structure **70**‡ (Figure 1) linking **67a** and **68a**. Similarly, structure **71**‡ models the V_2 to A_1 transformation between **68b** and **69b**. In the direction $V_1 \rightarrow V_2 \rightarrow A_1$, the activation energies are calculated to be 12.5 and 11.0 kcal/mol, respectively. Key geometric elements of the transition structures are depicted in Figure 1 and Table 1 (supporting information). Most revealing are the bond angles around the C═C centers undergoing bond breaking and bond making. The $V_1 \rightarrow V_2$ barrier maximum **70**‡ is characterized by an acetylene-like structure with C═C─C bond angles of 175.1 and 158.0°. Saddle point **71**‡ exhibits the same angle at 159.6° and closely

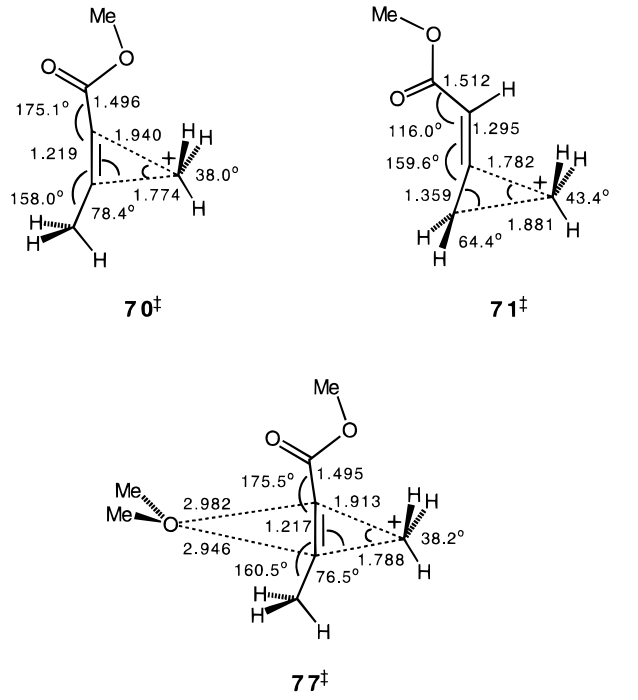


Figure 1. 6-31G* optimized transition states for the steps $V\hat{1} \rightarrow V\hat{2}$ (**67a** → **70**‡ → **68a** and **75a** → **77**‡ → **76a**) and $V\hat{2}$ → allyl (**68b** → **71**‡ → **69b**).

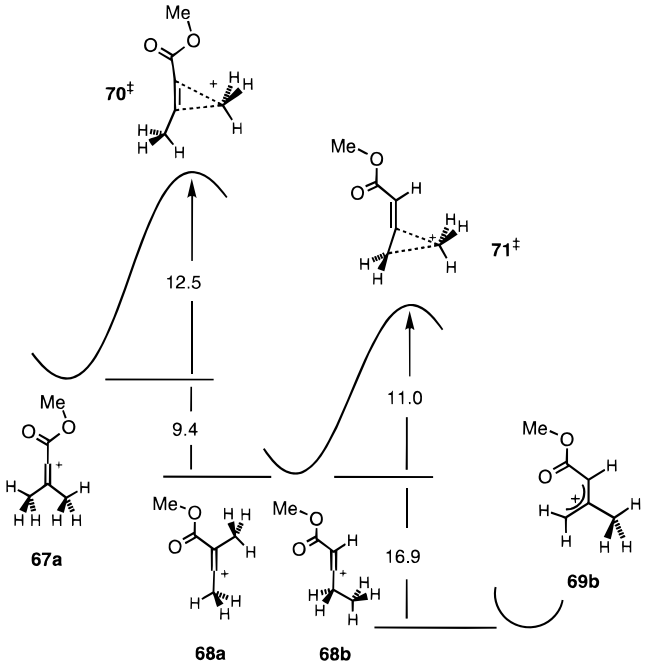


Figure 2. 6-31G* optimized hypersurface for the acyclic migrations $V\hat{1} \rightarrow V\hat{2} \rightarrow$ A1 (kcal/mol). Structures **68a** and **68b** are arbitrarily scaled to the same energy.

resembles the approximate transition state for hydride migration connecting the 2-propenyl and allyl cations.[55]

Figure 2 depicts the 6-31G* $V_1 \rightarrow V_2 \rightarrow A_1$ energy profile for the acyclic transformations. Among other things, it illustrates that the barrier height for the initial 1,2-shift between V_1 and V_2 (**70**‡) is of the same order of magnitude as the transition state **71**‡ leading to the allyl cation. The implication of the structural and energetic analysis is clear. Where ring strain is likely to play a role, ring expansion will be favored

(53) Sustmann, R.; Williams, J. E.; Dewar, M. J. S.; Allen, L. C.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1969**, *91*, 5350.

(54) Siehl, H.- U.; Müller, T.; Gauss, J.; Buzek, P.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1994**, *116*, 6384.

(55) Radom, L., Hariharan, P. C.; Pople, J. A.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1973**, *95*, 6531.

Table 2. Normalized Distributions of V_1, V_2, and Allyl Products from Reactions of α-Diazo-β-hydroxy Esters with BF_3·OEt_2 in Various Solvents

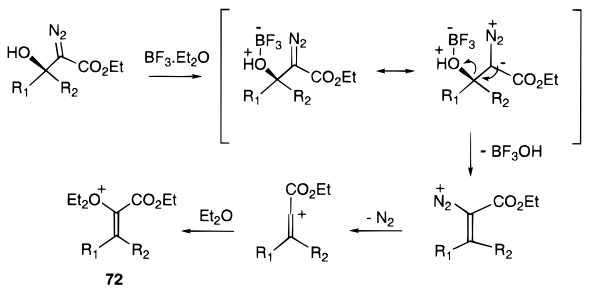
solvent and cationic intermediates	normalized product ratios, % (total yield, %)			
	10	**25**	**36**	**43**
		Benzene		
V_1	6	33		22
V_2		41	100	70
A_1	94	26		8
	(92)	(76)	(89)	(94)
		Pentane		
V_1		36		34
V_2		53		53
A_1	100	11		13
	(75)	(79)		(76)
		CH_3CN		
V_1	6	90		15
V_2	19	10		85
A_1	75			
	(81)	(61)		(72)

and ring contraction will be disfavored. As smaller rings are involved, the first migration barrier will fall relative to the second.

Thus, cyclohexane **10** (**64a**) manages expansion to the seven-ring V_2 chair **65a** and subsequent contraction to six-ring allyl cation **66a** with ease. Five-ring **25** (**64b**) negotiates the same path but surmounts the $V_2 \rightarrow A_1$ barrier with greater difficulty as indicated by significant capture of V_1 and V_2. The uniquely strained cyclobutane **66b** appears to ring expand rapidly with a calculated energy gain of 8.2 kcal/mol (Table 1, supporting information). Then, however, it is trapped at V_2 unable to pay the energetic price required to reach or mimic the near linear transition state **71**‡. The acyclic precursor **43** differs from the cyclic species in two important ways. First, it carries an intramolecular phenyl group positioned to dissipate cationic charge in subsequent intermediates by entropically favorable ring closure. Second, it proceeds to linear vinyl cations analogous to **67** and **68** with steric features absent in the cyclic cases. An array of products partitioned along all three $V_1/V_2/A_1$ channels is the consequence.

Possible Role of Et_2O in BF_3·OEt_2. The most striking structural feature of the optimized cyclic V_2 vinyl cations **65a**−**c** is ring distortion in response to the cation's effort to linearize. The strained seven-, six-, and five-membered rings display $C{=}C^+{-}CH_2$ bond angles of 167.8, 156.1 and 146.7°, respectively (Table 1, supporting information). Acycles **68a** and **b**, on the other hand, enjoy outstretched angles of 175.4 and 177.1°. While the distorted gas phase cyclic structures may have transient existence in the reactions of α-diazo-β-hydroxy esters, an important stabilizing factor can be envisaged in the following sequence of events.[56]

Scheme 2



In order to promote the transformation of diazoester, BF_3·OEt_2 is obligated to relinquish an equivalent of diethyl ether.

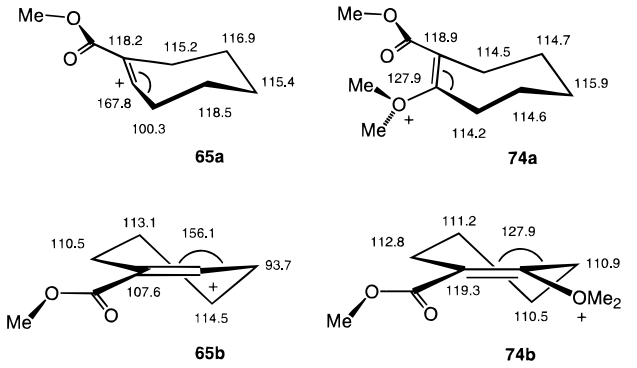
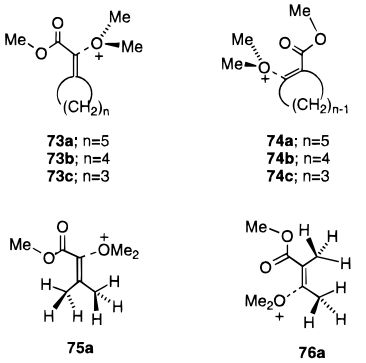


Figure 3. Comparison of 6-31G* optimized endocyclic ring ring angles for unsolvated and solvated V_2 cation intermediates.

Given the cationic nature of the subsequent intermediates, the ether is most likely retained within the substrate solvent cage. With the release of dinitrogen and the formation of a vinyl cation, ether can serve as a cation coordinating agent to give the vinyl cation equivalent (**72**) of the classical and commercially available Meerwein reagent, $[(Et)_3O^+][BF_4^-]$. One consequence of this interpretation is that without an abundance of easily exchanged ether, BF_3 will remain strongly coordinated to the hydroxide ion.



To examine other possible consequences of ether-vinyl cation coordination, structures **73**−**76** incorporating a molecule of dimethyl ether were likewise optimized at the 6-31G* level. The disturbing geometric distortions within the cyclic vinyl cations are abated. The 147−168° $C{=}C^+{-}C$ angles of the cyclic carbocations have dropped to 117−127° for rings **74a**−**c** (Table 3, supporting information). Bond angles are slightly larger than those found in normal alkenes (**75a** 133.3°), reflecting the presence of a solvated rather than a covalently bound vinyl cation. At the same time, the relatively normal ring geometries for the solvated structures are in line with stability expectations for compounds engaging in both unimolecular and bimolecular reactions. Figure 3 underscores the point by comparing ring angles for solvated and unsolvated 6-31G* V_2 vinyl cations.

Another outcome of the hypothesis of ether as reagent in the present series of reactions is that V_1 vinyl cations are no longer linear. The $C{=}C^+{-}C$ angles for **73a**−**c** fall within the range 130−135° in contrast to 171−173° for the gas phase counterparts **64a**−**c** (Table 1 and 3, supporting information). Likewise, the solvated acyclic V_2 cation **76a** sustains a bond angle for the cationic moiety of 132.1° *vs* 175.4° for the unsolvated analog **68a**. Furthermore, in response to ether participation, the very tight bond lengths around uncoordinated $C{=}C^+$ are relaxed considerably. For example, the $CH_2C^+{=}C(CO)CH_2$ fragment in **65a** displays bond distances of 1.415, 1.272, and 1.531 Å that shift to 1.509, 1.321, and 1.524 Å in **74a.**

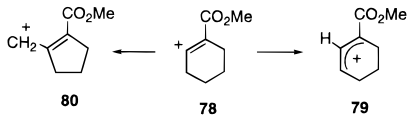
The satisfying structural characteristics of the solvated vinyl cations are complemented by solvation energies from 43−68 kcal/mol (E_{solv}(**a**−**b**/**c**), Table 3, supporting information). Not surprisingly, the value increases with decreasing ring size. While the differential stabilization is moderate for the V_1 series **73a**−**c** (ΔE_{solv} = 3.7 and 6.7 kcal/mol), it is substantial for the cyclic V_2's, **74a**−**c** (7.4 and 22.2 kcal/mol). The operation of a kinetic component for the product distributions of Table 2 is again supported by the E_{rel}'s of Table 3 (supporting information). A completely thermodynamic bias would predict six-ring **10** and five-ring **25** to deliver only V_1 and V_2 products, respectively, in contrast to the experimental outcomes.

The ether solvated transition state analog of **70**‡, **77**‡, has been located with the geometric variables depicted at the bottom of Figure 1. Inspection of the two structures demonstrates a very similar geometry with the molecule of dimethyl ether in **77**‡ at a distance of nearly 3.0 Å. Migration of the methyl has obviously displaced the solvent as one might expect for an easily dislodged leaving group. The calculated stabilization of **77**‡ by the ether molecule is 8.8 kcal/mol (E_{solv}, Table 3, supporting information). This is rather meager when compared with the 45−68 kcal/mol found for solvent association with various vinyl cations in the ground state. We do not take this to imply that the barrier for migration from **75a** to **77**‡ is 57.5 kcal/mol (Table 3, supporting information). Clearly, solvent orientation *trans* to the migrating group is a less favorable location than other centers around the transition state. These have not been explored in the present study.

Concluding Remarks

Boron trifluoride etherate promoted transformation of α-diazo-*β*-hydroxy esters in various solvents leads to a diversity of products. Vinyl cation formation, rearrangement ($V_1 \rightarrow V_2 \rightarrow$ allyl) and concomitant carbenium ion trapping along the reaction pathway accommodate both product structure and distribution from the different reaction channels. The driving force for many carbocation rearrangements, including vinyl cations, is generally considered to be formation of the more stable carbenium ion. For example, the principle has been applied to vinyl triflate solvolysis[25] and the formation of allyl cations from acetylenes in FSO_3HSBF_5 at low temperature.[57] In the present instance, our 6-31G* calculations likewise predict increasing stability for $V_1 \rightarrow V_2 \rightarrow A_1$. However, diversion of the products early in the pathway prior to formation of the final A_1 carbenium ions suggests the operation of a kinetic component as well. In the cyclic cases, the energy barriers corresponding to $V_1 \rightarrow$ **70**‡ and $V_2 \rightarrow$ **71**‡ (Figure 2) are expected to be raised by comparison with the acyclic system permitting the trapping of V_1 and V_2 as recorded in Table 2.

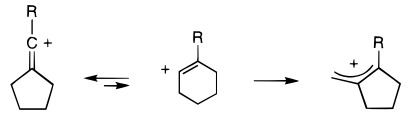
Support for the kinetic interpretation is found in the observation that hydride and alkyl groups alike are known to participate in 1,2-shifts to the vinyl cation C═C$^+$ to produce allyl cations.[2c,d] Yet to our knowledge, no 1,2-migrations in which the resultant allylic ion is primary have been reported. By contrast, each of the vinyl cation precursors studied here (**10**, **25**, and **43**) leads to such an intermediate (Scheme 1). A 1,2-hydride shift in **78** (i.e., **10** and **25**) would have yielded the secondary internal allyl cation **79.** That CH_2 has shifted instead of H, in spite of the strain-inducing ring contraction to **80**, argues for a decisive stereoelectronic component in the presumably concerted process. The orientation of migrating methyl in **71**‡ (Figure 1) illustrates the planar array of atoms required to achieve productive orbital overlap. Saturated ring carbons α to the cationic center in cycles such as **78**, but not the attached hydrogens, can assume a relatively low energy transition state geometry in accord with a kinetic driving force for the reaction.



80 **78** **79**

A novel feature of the cationic intermediates in the present work is substitution by the electron withdrawing carboethoxy moiety. One implication concerns the fact that vinyl cations rearrange both by ring contraction and expansion.[2] Methyl analogs **81a** and **82a**, for example, have been shown to interconvert under solvolytic conditions in EtOH and TFE. In this case, transformation to allyl cation product **83a** was not observed.[58] The differences underscore one of the characteristics of *destabilized* vinyl cation intermediates. Whereas the methyl substituted cations are nearly isoenergetic, the corresponding equilibrium for carbomethoxy derivatives **81b** and **82b** lies far to the right. The calculated energy difference of −3.1 kcal/mol (Table 1, supporting information) translates to an approximate relative population of 1:200 (0.5:99.5%), respectively. It has been estimated that the effectiveness of α-substituents to stabilize a vinyl cation follow the order $C_6H_5 \gg CH_2{=}CH_2 \gg CH_3 \gg H$, where the overall gap is 60 kcal/mol. Of this, the CH_3/H difference amounts to 25 kcal/mol.[59] Obviously, the CO_2Me occasions still greater destabilization.

Consistent with the destabilizing effect of CO_2R, we propose that generation of vinyl cations in the presence of ether leads to long-lived oxonium intermediates analogous to Meerwein reagents (e.g., **73**−**76**). Cation-solvent association accompanied by significant geometry variation applies as well to other vinyl cations in the presence of basic but weak nucleophiles. Under favorable conditions, complex formation ought to be perceived by techniques such as NMR. Conceivably, the unexpectedly poor agreement between measured and calculated ^{13}C chemical shift for the trivalent carbon in the cyclopropylcyclopropylidenemethyl cation stems from a bent geometry in the presence of FSO_3H.[54]

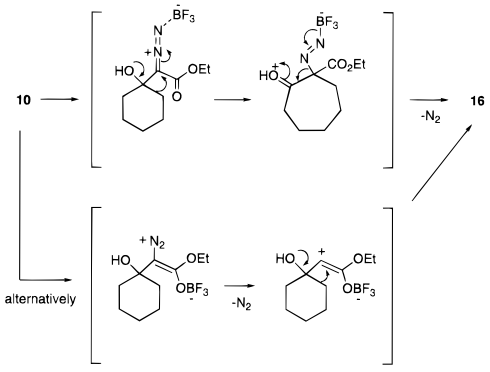


81a; R = Me
81b; R = CO_2Me

82a **83a**

Finally, we have discussed the formation of allyl cations from **10**, **25**, and **43** as proceeding through a pair of sequential 1,2-

(56) Variations on this mechanism, especially when catalytic BF_3 is used have been suggested by the reviewers and are shown below:



(57) Olah, G. A.; Mayr, H. *J. Am. Chem. Soc.* **1976**, *98*, 7333.

(58) Hanack, M.; Fuchs, K. A., unpublished; reported in ref 2d, pp 464−465.

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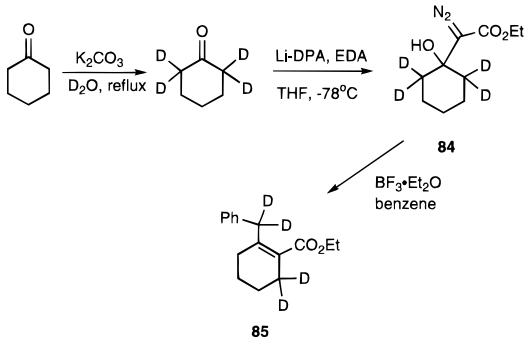
shifts. In principle, allyl cations can arise directly from V_1 by means of a 1,3-carbon shift, thereby avoiding altogether the strained cyclic vinyl cations V_2. Although 1,4-halogen and 1,5-hydride migrations to vinyl cations are known,[2] 1,3-shifts do not seem to have been reported. Indeed, rearrangement of the putative vinyl cation obtained by adding *tert*-butyl cation to 2-butyne has been interpreted as a double 1,2-methyl shift, the 1,3-methyl migration rejected by deuterium labeling.[60] To test for the possible operation of a 1,3-trans-formation in **10**, D-labels were introduced into **84** starting from cyclohexanone.



BF_3·OEt_2 promoted rearrangement led to a single deuterated product. Compound **85** with the $CD_2C(=)CO_2Et$ label is consistent only with two sequential 1,2-shifts. A 1,3-rearrangement to an allyl cation would have afforded the unobserved $CD_2C(=)CD_2Ph$ pattern.

Experimental Section

Proton and carbon magnetic resonance spectra were taken on a Varian EM 390, a Bruker AC 200, and a GE QE-300 spectrometer, and the chemical shifts are reported on the δ scale relative to tetramethylsilane. ^{13}C-NMR spectra were recorded on a GE QE-300 75 MHz spectrometer. Mass spectra were determined with a VG MM-7070S mass spectrometer at an ionizing voltage of 70 eV. Melting points were determined on a Thomas-Hoover capillary melting point apparatus and are uncorrected. Unless otherwise noted, all reactions were performed in oven dried glassware under an atmosphere of dry argon. Solutions were evaporated under reduced pressure with a rotary evaporator, and the residue was flash chromatographed on a silica gel column using a hexane−ethyl acetate mixture as the eluent unless specified otherwise.

Product Elucidation Studies. Some of the products obtained from the reaction of the α-diaazo-β-hydroxy esters with BF_3·OEt_2 correspond to known compounds. These include lactones **11**,[61] **23**,[62] and **24**,[62] and esters **16**,[63] **17**,[64] and **37**.[65] The spectral properties of these compounds have been compared to independently synthesized material and were identical in every detail.

General Procedure for the Preparation of Ethyl 2-Diazo-3-hydroxy Carboxylates. A cold (−10 °C) solution of lithium diisopropylamide [prepared by the addition of *n*-butyllithium in hexane (20 mL of a 2.5 M solution) to a solution of diisopropylamine (5.05 g) in THF (30 mL)] was added during 30 min to a stirred solution of the appropriate ketone (41 mmol) and ethyl diazoacetate (41 mmol) at −78 °C. The mixture was allowed to stir at −78 °C for 2 h at which time the reaction was quenched with a saturated NH_4Cl solution and extracted with ether. The combined organic extracts were washed with saturated aqueous $NaHCO_3$ solution and brine, dried over anhydrous $MgSO_4$, and concentrated under reduced pressure. The residue was subjected to flash silica gel chromatography to afford the pure ethyl 2-diazo-3-hydroxy carboxylate.

Reaction of Ethyl 2-Diazo-2-(1-hydroxycyclohexyl)acetate (10) with Boron Trifluoride Etherate. Ethyl 2-diazo-2-(1-hydroxycyclohexyl)acetate (**10**) was prepared in 88% yield as a yellow oil using 2.0 g (20 mmol) of cyclohexanone: IR (neat) 3473, 2086, 1687, 1296, and 1104 cm^{-1}; ^{1}H-NMR (300 MHz, $CDCl_3$) δ 1.29 (t, 3H, J = 7.1 Hz), 1.33−1.91 (m, 10H), 3.51 (s, 1H), and 4.24 (q, 2H, J = 7.1 Hz); ^{13}C-NMR (75 MHz, $CDCl_3$) δ 14.0, 14.3, 21.9, 24.3, 25.1, 27.5, 36.3, 60.6, 70.1, and 167.1.

To a cold (0 °C) mixture of 4.7 mL (37 mmol) of BF_3·Et_2O in 40 mL of pentane was added dropwise 5.30 g (25 mmol) of diazoester **10** in 20 mL of pentane. After stirring for 2 h, the reaction was quenched with a saturated $NaHCO_3$ solution, extracted with ether, washed with brine, and dried over $MgSO_4$. Concentration of the mixture under reduced pressure followed by silica gel column chromatography gave 2.60 g (75%) of tetrahydro-1(3*H*)-isobenzofuranone (**11**) as a white solid: mp 50−51 °C (lit.[61] mp 53−54 °C); IR (CCl_4) 1750, 1679, 1438, 1240, and 1021 cm^{-1}; ^{1}H-NMR (90 MHz, $CDCl_3$), δ 1.45−2.06 (m, 4H), 2.07−2.41 (m, 4H), and 4.68 (s, 2H). Anal. Calcd for $C_8H_{10}O_2$: C, 69.55; H, 7.30. Found: C, 69.50; H, 7.30.

To a cold (5 °C) mixture of 0.90 mL (7.1 mmol) of BF_3·Et_2O in 5 mL of benzene was added dropwise 1.0 g (4.7 mmol) of diazoester **10** in 5 mL of benzene. After stirring for 2 h, the reaction was quenched with a saturated aqueous $NaHCO_3$ solution. The mixture was extracted with ether, and the extracts were washed with brine, dried over $MgSO_4$, and concentrated under reduced pressure. The residue was purified by flash silica gel chromatography to give 0.05 g (6%) of α-fluorocyclohexylideneacetate (**13**): ^{1}H-NMR (90 MHz, $CDCl_3$) δ 1.30 (t, 3H), 1.60 (m, 6H), 2.32 (m, 2H), 2.70 (m, 2H), and 4.25 (q, 2H); *m*/*e* 186 (61), 158, 157, 141, 139, 104, and 91; GC purity: ≥99%. Further elution afforded 0.85 g (74%) of ethyl 2-benzyl-cyclohex-1-enecarboxylate (**12**) as a pale yellow oil: IR (neat) 2934, 1706, 1223, and 1046 cm^{-1}; ^{1}H-NMR (300 MHz, $CDCl_3$) δ 1.27 (t, 3H, J = 7.1 Hz), 1.51−1.64 (m, 4H), 1.99−2.03 (m, 2H), 2.33−2.42 (m, 2H), 3.71 (s, 2H), 4.20 (q, 2H, J = 7.1 Hz), and 7.23 (m, 5H); ^{13}C-NMR (75 MHz, $CDCl_3$) δ 14.1, 14.2, 22.0, 22.1, 26.6, 30.2, 40.6, 60.0, 125.8, 126.2, 128.1, 139.7, 145.4, and 169.1. Anal. Calcd for $C_{16}H_{20}O_2$: C, 78.65; H, 8.25. Found: C, 78.60; H, 8.25. Further elution of the silica gel column afforded 0.08 g (12%) of tetrahydro-1(3*H*)-isobenzofuranone (**11**).

To a cold (10 °C) mixture of 0.78 mL (6.3 mmol) of BF_3·Et_2O in 3.0 mL of *p*-xylene was added dropwise 0.90 g (4.24 mmol) of diazoester **10** in 3.0 mL of *p*-xylene. After stirring for 2 h, the reaction was quenched with a saturated $NaHCO_3$ solution, extracted with ether, washed with brine, and dried over $MgSO_4$. Concentration under reduced pressure followed by column chromatography on silica gel gave 0.54 g (47%) of ethyl 2-(2,5-dimethylbenzyl)-cyclohex-1-enecarboxylate (**14**) as a pale yellow oil: IR (neat) 1708, 1630, 1496, 1220, and 1043 cm^{-1}; ^{1}H-NMR (300 MHz, $CDCl_3$) δ 1.24 (t, 3H, J = 7.0 Hz), 1.52−1.65 (m, 4H), 1.94−1.96 (m, 2H), 2.21 (s, 3H), 2.27 (s, 3H), 2.33−2.37 (m, 2H), 3.72 (s, 2H), 4.17 (q, 2H, J = 7.0 Hz), and 6.95 (m, 3H); ^{13}C-NMR (75 MHz, $CDCl_3$) δ 14.1, 19.1, 20.9, 22.1, 22.2, 26.7, 30.3, 37.9, 59.9, 126.4, 126.5, 129.5, 129.7, 133.2, 135.0, 137.6, 145.6, and 169.1. Anal. Calcd for $C_{18}H_{24}O_2$: C, 79.36; H, 8.89. Found: C, 79.04; H, 8.73.

To a cold (0 °C) mixture of 0.90 mL (7.1 mmol) of BF_3·Et_2O in 5 mL of acetonitrile was added dropwise 1.0 g (4.7 mmol) of diazoester **10** in 5 mL of acetonitrile. After stirring for 2 h, the reaction was quenched with a saturated aqueous $NaHCO_3$ solution. The mixture was extracted with ether, and the extracts were washed with brine, dried over $MgSO_4$, and concentrated under reduced pressure. The residue was purified by flash silica gel chromatography to give 0.040 g (5%) of an inseparable mixture of the *E*- and *Z*-isomers of diene **17**:[64] ^{1}H-NMR (90 MHz, $CDCl_3$) δ 1.30 (t, 2 × 3H), 1.75 (m, 2 × 2H), 2.15 (m, 2 × 2H), 2.40 (m, 2H), 3.00 (m, 2H), 4.07 (q, 2 × 2H), 5.47 (s, 1H), 5.60 (s, 2H), 6.20 (m, 2 × 1H), and 7.50 (m, 1H). Anal. Calcd for $C_{10}H_{14}O_2$: C, 72.26; H, 8.49. Found: C, 72.15; H, 8.55. Further elution gave 0.130 g (15%) of 2-hydroxy-1-cycloheptenecarboxylate (**16**):[63] ^{1}H-NMR (90 MHz, $CDCl_3$) δ 1.10−2.70 (m, 5 × 2H), 1.25 (t, 3H), 3.50 (t, 0.65H), 4.16 (q, 2H), and 12.40 (s, 0.35H). Anal. Calcd

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for $C_{10}H_{16}O_3$: C, 65.19; H, 8.75. Found: C, 65.25; H, 8.70. Further elution afforded 0.15 g (23%) of lactone **11** as well as 0.40 g (38%) of ethyl 2-acetamidomethyl-1-cyclohexene carboxylate (**15**): ^{1}H-NMR ($CDCl_3$) δ 1.25 (t, 3H, J = 7.1 Hz), 1.40−1.70 (m, 4H), 2.00 (s, 3H), 2.10−2.30 (m, 4H), 3.95 (d, 2H), 4.15 (q, 2H, J = 7.1 Hz), and 6.20 (brs, 1H, NH); ^{13}C-NMR ($CDCl_3$) δ 14.2, 20.0, 21.8, 23.3, 26.1, 30.9, 42.3, 65.8, 127.9, 147.1, 168.6, and 169.8; *m/e* 225 (16), 179 (75), 151 (87). Anal. Calcd for $C_{12}H_{19}NO_3$: C, 63.98; H, 8.50; N, 6.22. Found: C, 63.95; H, 8.40; N, 6.25.

Preparation and Reaction of Ethyl 2-Diazo-2-(cyclohexenyl)-acetate (18) with Boron Trifluoride Etherate. To a cold (−5 to −10 °C) solution containing 2.12 g (10.0 mmol) of diazoester **10** in 40 mL of pyridine was added 6.13 g (40.0 mmol) of phosphoryl chloride with stirring. The resulting mixture was stirred for 6.5 h at 0 °C and was then allowed to warm to room temperature. The solution was filtered through a pad of Celite, extracted with pentane, washed with water, and dried over $MgSO_4$. Evaporation of the solvent gave 1.63 g (84%) of ethyl 2-diazo-2-(cyclohexenyl)acetate (**18**) as an orange oil which was sufficiently pure for use in the next step: IR (neat) 2925, 2071, and 1701 cm^{-1}; ^{1}H-NMR (90 MHz, $CDCl_3$) δ 1.25 (t, 3H, J = 7 Hz), 1.45−1.89 (m, 4H), 1.99−2.30 (m, 4H), 4.30 (q, 2H, J = 7 Hz), and 6.03−6.24 (m, 1H). Treatment of **18** with $BF_3{\cdot}Et_2O$ in the presence of benzene resulted only in nitrogen evolution and the formation of a complex mixture of products which did not contain any detectable quantities of ethyl 2-benzyl-cyclohex-1-enecarboxylate (**13**). A sample of ethyl 4,5-cyclohexa-1*H*-pyrazole-3-carboxylate (**19**) was prepared by heating a 1.10 g (5.66 mmol) sample of **18** in 30 mL of *n*-octane at 110 °C for 1 h. The mixture was cooled to room temperature and concentrated under reduced pressure, and the white crystalline solid that precipitated was recrystallized from hexane to give 650 mg (59%) of ethyl 4,5-cyclohexa-1*H*-pyrazole-3-carboxylate (**19**): mp 90−91 °C (lit.[43] mp 90−91 °C); IR (CCl_4) 3445, 3018, 1716, 1438, and 1211 cm^{-1}; ^{1}H-NMR (300 MHz, $CDCl_3$) δ 1.31 (t, 3H, J = 7.5 Hz), 1.65−1.9 (m, 4H), 2.59−2.87 (m,4H), 4.35 (q, 2H, J = 7.5 Hz), and 10.8 (brs, 1H, J = 7.5 Hz). Treatment of **19** with $BF_3{\cdot}Et_2O$ in the presence of benzene also failed to give any detectable quantities of ethyl 2-benzylcyclohex-1-enecarboxylate (**13**).

Reaction of Ethyl 2-Diazo-2-(1-hydroxy-2-methylcyclohexyl)-acetate (21) with Boron Trifluoride Etherate. Ethyl 2-diazo-2-(1-hydroxy-2-methylcyclohexyl)acetate (**21**) was obtained in 53% yield as a yellow oil by using 1.0 g (8.9 mmol) of 2-methylcyclohexanone: IR (neat) 3480, 2086, 1666, 1367, 1296, and 1104 cm^{-1}; ^{1}H-NMR (300 MHz, $CDCl_3$) δ 0.94 (d, 3H, J = 6.6 Hz), 1.27 (t, 3H, J = 7 Hz), 1.40−1.81 (m, 8H), 1.99−2.03 (m, 1H), 3.74, (s, 1H), and 4.22 (q, 2H, J = 7 Hz); ^{13}C-NMR (75 MHz, $CDCl_3$) δ 14.4, 15.9, 21.5, 25.3, 30.0, 33.9, 37.9, 38.2, 60.7, 71.8, and 167.7.

To a cold (5 °C) mixture containing 0.46 mL (3.7 mmol) of $BF_3{\cdot}Et_2O$ in 2.5 mL of benzene was added dropwise 570 mg (2.52 mmol) of diazoester **21** in 2.5 mL of benzene. After stirring for 2 h, the reaction was quenched with a saturated $NaHCO_3$ solution, extracted with ether, washed with brine, and dried over $MgSO_4$. The solvent was removed under reduced pressure, and the residue was chromatographed on a flash silica gel column. The major fraction contained 117 mg (18%) of ethyl 2-benzyl-6-methylcyclohex-1-enecarboxylate (**22**) as a pale yellow oil: IR (neat) 2924, 1707, 1449, 1218, and 1043 cm^{-1}; ^{1}H-NMR (300 MHz, $CDCl_3$) δ 1.04 (d, 3H, J = 7 Hz), 1.28 (t, 3H, J = 7 Hz), 1.32−1.89 (m, 4H), 1.92 (m, 4H), 2.74 (m, 2H), 3.48 (d, 1H, J = 14.2 Hz), 3.58 (d, 1H, J = 14.2 Hz), 4.23 (q, 2H, J = 7 Hz), and 7.69 (m, 5H); ^{13}C-NMR (75 MHz, $CDCl_3$) δ 14.2, 19.3, 20.2, 29.5, 30.2, 30.5, 40.8, 60.1, 125.9, 128.2, 128.8, 132.6, 139.7, 141.4, and 170.0. Anal. Calcd for $C_{17}H_{22}O_2$: C, 79.02; H, 8.59. Found: C, 79.13; H, 8.62.

To a cold (0 °C) mixture of 0.45 mL (3.7 mmol) of $BF_3{\cdot}Et_2O$ in 2.5 mL of nitromethane was added dropwise 550 mg (2.43 mmol) of diazoester **21** in 2.5 mL of nitromethane. After stirring for 2 h, the reaction was quenched with a saturated $NaHCO_3$ solution, extracted with ether, washed with brine, and dried over $MgSO_4$. Concentration under reduced pressure followed by flash silica gel chromatography afforded 290 mg (78%) of an inseparable 1:1 mixture of methyl lactones **23** and **24**:[62] IR (neat) 2932, 1743, 1672, 1446, and 1022 cm^{-1}; ^{1}H-NMR (300 MHz, $CDCl_3$) (compound **23**) δ 1.18 (d, 3H, J = 7.1 Hz), 1.67−1.89 (m, 4H), 2.18−2.21 (m, 2H), 2.51−2.54 (m, 1H), and 4.69 (s, 2H); (compound **24**) δ 1.40 (d, 3H, J = 6.7 Hz), 1.67−1.89 (m, 4H), 2.29−2.35 (m, 4H), and 4.90 (q, 1H, J = 6.7 Hz); ^{13}C-NMR (75 MHz, $CDCl_3$) (mixture) δ 17.7, 17.8, 18.6, 19.3, 21.0, 22.3, 23.4, 25.4, 29.9, 71.1, 78.7, 125.1, 129.2, 160.8, 164.7, 172.9, and 173.3; HRMS calcd for $C_9H_{12}O_2$ 152.0837, found: 152.0837.

Reaction of Ethyl 2-Diazo-2-(1-hydroxycyclopentyl)acetate (25) with Boron Trifluoride Etherate. Ethyl 2-diazo-2-(1-hydroxycyclopentyl)acetate (**25**) was prepared in 98% yield as a yellow oil by using 5.0 g of cyclopentanone (59.5 mmol) and 6.79 g of ethyl diazoacetate (59.5 mmol): IR (neat) 3466, 2086, 1687, and 1296 cm^{-1}; ^{1}H-NMR (300 MHz, $CDCl_3$) δ 1.30 (t, 3H, J = 7.1 Hz), 1.67−1.98 (m, 6H), 1.99−2.11 (m, 2H), 3.29 (s, 1H), and 4.25 (q, 2H, J = 7.1 Hz); ^{13}C-NMR (75 MHz, $CDCl_3$) δ 14.2, 22.8, 39.1, 60.6, 78.3, and 166.9.

To a cold (5 °C) solution containing 0.74 mL (6.0 mmol) of $BF_3{\cdot}Et_2O$ in 3 mL of benzene was added dropwise 740 mg (3.73 mmol) of diazoester **25** in 3 mL of benzene. After stirring for 2 h, the reaction was quenched with a saturated $NaHCO_3$ solution, extracted with ether, washed with brine, and dried over $MgSO_4$. Concentration under reduced pressure and flash column chromatography on silica gel gave 71 mg (21%) of ethyl 2-phenylcyclohex-1-enecarboxylate (**26**): IR (neat) 2932, 1695, 1246, and 1051 cm^{-1}; ^{1}H-NMR (300 MHz, $CDCl_3$) δ 0.83 (t, 3H, J = 7.1 Hz), 1.75 (m, 4H), 2.40 (m, 4H), 3.86 (q, 2H, J = 7.1Hz), and 7.22 (m, 5H); ^{13}C-NMR (75 MHz, $CDCl_3$) δ 13.5, 21.9, 22.5, 26.6, 32.6, 60.0, 126.8, 126.9, 127.9, 128.0, 143.5, 145.5, and 170; *m/e* 230 (M^+), 201, 184 (base), 156, 129, 115 and 91. Anal. Calcd for $C_{15}H_{18}O_2$: C, 78.22; H, 7.88. Found: C, 77.91; H, 7.66.

The minor product isolated from the silica gel column chromatography column (48 mg, 16%) was identified as ethyl 2-benzylcyclopent-1-enecarboxylate (**27**) on the basis of its spectral properties: IR (neat) 2954, 1702, 1637, 1253, and 1101 cm^{-1}; ^{1}H-NMR (300 MHz, $CDCl_3$) δ 1.31 (t, 3H, J = 7.0 Hz), 1.68−1.81 (m, 2H), 2.38 (m, 2H), 2.67 (m, 2H), 3.95 (s, 2H), 4.23 (q, 2H, J = 7.0 Hz), and 7.23 (m, 5H); ^{13}C-NMR (75 MHz, $CDCl_3$) δ 14.3, 21.3, 33.7, 36.1, 37.8, 59.8, 126.1, 128.3, 128.8, 139.2, 156.8, and 166.2; *m/e* 230 (M^+), 201, 184 (base), 155, 129, 115, 91, and 77. Anal. Calcd for $C_{15}H_{18}O_2$: C, 78.22; H, 7.88. Found: C, 78.09; H, 7.56.

The reaction was repeated using $BF_3{\cdot}Et_2O$ which had not been distilled. A solution containing 1.0 g (5.05 mmol) of diazoester **25** in 10 mL of benzene was added dropwise during 20 min to a solution of 0.93 mL (7.6 mmol) of $BF_3{\cdot}Et_2O$ in 10 mL of benzene kept under vigorous magnetic stirring at 5 °C under a nitrogen blanket. After stirring for 15 min, the reaction mixture was diluted with a saturated $NaHCO_3$ solution and extracted with EtOAc. The combined organic phases were washed with brine and dried over anhydrous Na_2SO_4. After evaporation of the solvent, the residue was submitted to medium pressure chromatography eluting with light petroleum ether. In addition to compounds **26** (13%) and **27** (20%), 0.21 g (25%) of ethyl α-fluorocyclopentylidene acetate (**28**) was obtained: ^{1}H-NMR ($CDCl_3$) δ 1.35 (t, 3H, J = 7.1 Hz), 1.75 (m, 4H), 2.55 (m, 2H), 2.70 (m, 2H), and 4.30 (q, 2H, J = 7.1 Hz); ^{13}C-NMR ($CDCl_3$) δ 12.7, 25.6, 26.9, 30.5, 30.9, 61.5, 139.0, 141.0 (CF═C), 141.3, 143.9, (CF═C), and 160.9; *m/e* 172 (M^+), 144 (base), 127, 115, 99, 79, and 59; GC purity: ≥99%.

Further elution with the same solvent afforded 0.22 g (18%) of ethyl 2-fluoro-1-cyclohexene carboxylate (**29**): ^{1}H-NMR ($CDCl_3$) δ 1.26 (t, 3H, J = 7.1 Hz), 1.57 (m, 2H), 1.70 (m, 2H), 2.26 (m, 4H), 4.13 (q, 2H, J = 7.1 Hz); ^{13}C-NMR ($CDCl_3$) δ 14.1, 21.7, 22.0, 24.3, 26.7, 27.2, 60.2, 108.0 (CF═C), 162.6, 165.7 (CF═C), 168.2; *m/e* 172 (M^+), 144, 127 (base), 99, and 79; GC purity: ≥99%.

When the reaction was carried out in pentane, in addition to compounds **28** (28%) and **29** (42%), it was also possible to isolate ethyl 2-fluoromethyl-1-cyclopentenecarboxylate (**30**) (9%): ^{1}H-NMR ($CDCl_3$) δ 1.25 (t, 3H, J = 7.1 Hz), 1.82 (m, 2H), 2.60 (m, 4H), 4.15 (q, 2H, J = 7.1 Hz), and 4.40 (s, 2H); ^{13}C-NMR ($CDCl_3$) δ 14.2, 21.5, 29.6, 33.8, 37.2, 60.5, 129.0 (FCH_2C═C), 159.6 (FCH_2C═C), and 166.8; *m/e* 172 (M^+), 170, 142, 127, 124, 114, 86, 68 (base), and 55. Anal. Calcd for $C_{15}H_{19}O_2$: C, 77.89; H, 8.28. Found: C, 77.90; H, 8.30.

The reaction of **25** was also carried out in acetonitrile. A solution of 1.0 g (5.05 mmol) of **25** in 15 mL of acetonitrile was added dropwise during 20 min to a solution containing 0.93 mL (7.6 mmol) of $BF_3{\cdot}Et_2O$ in 15 mL of acetonitrile kept under vigorous magnetic stirring at 0 °C under a nitrogen atmosphere. After stirring for 15 min, the reaction

mixture was diluted with a saturated $NaHCO_3$ solution and extracted with ethyl acetate. The combined organic phase was washed with brine and dried over anhydrous Na_2SO_4. After evaporation of the solvent, the residue was submitted to flash silica gel chromatography using a 85:15 light petroleum−ethyl acetate mixture. The major fraction isolated from the column contained 0.50 g (55%) of ethyl α-acetamidocyclopentylidene acetate (**31**): ^{1}H-NMR ($CDCl_3$) δ 1.10 (t, 3H, J = 7.1 Hz), 1.45 (m, 2H), 1.95 (s, 3H), 2.15 (m, 2H), 2.90 (m, 2H), 4.10 (q, 2H, J = 7.1 Hz), and 11.40 (br s, 1H, NH); ^{13}C-NMR ($CDCl_3$) δ 13.6, 21.2, 21.3, 23.7, 27.9, 59.6, 103.8 (C═CN), 151.5 (C═CN), 168.1 (CON), and 169.3 (CO_2); *m*/*e* 211 (M^+), 165 (base), 137, 123, 96, 68, and 55. Anal. Calcd for $C_{11}H_{17}NO_3$: C, 62.54; H, 8.11; N, 6.63. Found: C, 62.50; H, 8.10; N, 6.70. Further elution with the same solvent resulted in 0.04 g (6%) of ethyl 2-acetamido-1-cyclohexene carboxylate (**32**): ^{1}H-NMR ($CDCl_3$) δ 1.25 (t, 3H, J = 7.1 Hz), 1.80 (m, 4H), 1.95 (s, 3H), 2.57 (m, 4H), 4.20 (q, 2H, J = 7.1 Hz), and 6.35 (br s, 1H, NH); ^{13}C-NMR ($CDCl_3$) δ 14.1, 21.2, 33.5, 37.3, 37,8, 59.9, 129.8 (C═CN), 155.5 (C═CN), 165.8 (CON), and 169.9 (CO_2); *m*/*e* 211 (M^+), 168, 140, 123 (base), 94, 79, and 43. Anal. Calcd for $C_{11}H_{17}NO_3$: C, 62.54; H, 8.11; N, 6.63. Found: C, 62.50; H, 8.15; N, 6.65.

Reaction of Ethyl 2-Diazo-2-(1-hydroxycyclobutyl)acetate (36) with Boron Trifluoride Etherate. Ethyl 2-diazo-2-(1-hydroxycyclobutyl)acetate (**36**) was obtained in 83% yield as a yellow oil by starting with 0.72 g (10 mmol) of cyclobutanone: IR (neat) 2090, 1682, 1301, and 1118 cm^{-1}; ^{1}H-NMR (300 MHz, $CDCl_3$) δ 1.19 (t, 3H, J = 7.2 Hz), 1.53−1.62 (m, 1H), 1.79−1.87 (m, 1H), 2.18−2.32 (m, 4H), 3.83 (brs, 1H), and 4.14 (q, 2H, J = 7.2 Hz); ^{13}C-NMR (75 MHz, $CDCl_3$) δ 12.9, 14.1, 35.1, 60.6, 71.9, and 166.2.

A solution of 0.461 g (2.5 mmol) of **36** in 2.5 mL of benzene was added dropwise during 30 min to a magnetically stirred solution of 0.46 mL (3.74 mmol) of freshly distilled BF_3·Et_2O in 2.5 mL of benzene under nitrogen at 5 °C. Stirring was continued for 2.5 h after which a saturated $NaHCO_3$ solution was added, and the resulting mixture was extracted with ethyl acetate. The combined organic phases were washed with brine and dried over anhydrous $MgSO_4$. Concentration of the mixture under reduced pressure followed by flash silica gel column chromatography gave 0.276 g (51%) of ethyl 2-phenylcyclopent-1-enecarboxylate (**37**):[65] IR (neat) 1703, 1591, 1114, and 1042 cm^{-1}; ^{1}H-NMR (300 MHz, $CDCl_3$) δ 1.11 (t, 3H, J = 7.1 Hz), 1.99 (pent, 2H, J = 7.6 Hz), 2.85 (m, 4H), 4.08 (q, 2H, J = 7.1Hz), and 7.31 (m, 5H); ^{13}C-NMR (75 MHz, $CDCl_3$) δ 13.9, 21.9, 35.1, 40.1, 59.9, 127.6, 127.7, 127.8, 129.3, 137.1, 153.0, and 166.3; HRMS calcd for $C_{14}H_{16}O_2$ 216.1150, found 216.1164. Compound **37** was closely followed by a small amount (0.022 g, 5%) of the fluoro derivative **38**. Further elution with the same solvent afforded 0.125 g (32%) of β-ketoester **39** whose spectral data were identical to that of authentic ethyl 2-oxocyclopentanecarboxylate.

Reaction of 1-(Ethoxycarbonyldiazomethyl)-2-phenylisopropyl Alcohol (43) with Boron Trifluoride Etherate. A cold (−78 °C) solution of lithium diisopropylamide [prepared by the addition of *n*-butyllithium in hexane (56.0 mL of a 1.0 M solution) to a solution of diisopropylamine (6.72 g, 66.5 mmol) in THF (30 mL)] was added during 2 h to a stirred solution of 6.33 g (47.2 mmol) of phenylacetone and 5.77 g (50.6 mmol) of ethyl diazoacetate at −78 °C under an argon atmosphere. After the addition was complete, 5 mL of acetic acid in 25 mL of ether at −78 °C was added, and the reaction mixture was allowed to warm to room temperature. Water was then added, the organic phase was separated, and the aqueous layer was extracted with chloroform. The combined organic layer was washed with brine and dried over anhydrous sodium sulfate. After evaporation of the solvent, the residue (10.5 g) was chromatographed on alumina (activity IV) with a pentane−ether mixture to give 9.74 g (83%) of **43**: IR ($CHCl_3$) 3445 (OH), 2080 (−C═N), 1655 cm^{-1} (CO); ^{1}H-NMR ($CDCl_3$) δ 1.20−1.55 (6H, m), 3.10 (2H, s), 3.90 (1H, s), 4.25 (2H, q, J = 8.5 Hz), and 7.25 (5H, m).

A solution of 1.70 g (6.85 mmol) of **43** in 10 mL of benzene was added dropwise during 30 min to a magnetically stirred solution of 1.38 mL (11.17 mmol) of freshly distilled BF_3·Et_2O in 10 mL of benzene under nitrogen at 5 °C. Stirring was continued for 10 min after which a saturated sodium hydrogen carbonate solution was added, and the resulting mixture was extracted with ethyl acetate. The combined organic phases were washed with brine and dried over anhydrous sodium sulfate. After evaporation of the solvent, the residue (1.65 g) was submitted to flash chromatography on silica gel using a pentane−ether mixture to give 0.396 g (26%) of the fluoro derivative **44**: IR ($CHCl_3$) 1720 (CO), 1670 cm^{-1} (C═C); ^{1}H-NMR ($CDCl_3$) δ 1.25 (3H, t), 2.45 (3H, d, J = 21 Hz), 3.75 (2H, d, J = 3.8 Hz), 4.20 (2H, q), 7.30 (5H, m); *m*/*e* 222 (25), 176, 147, 129, and 91; GC purity ≥99%. Following elution with the same solvent yielded a mixture (0.17 g) containing both the fluoro derivatives **44** and **45** [NMR **45**: ^{1}H-NMR ($CDCl_3$) δ 1.35 (3H, t), 2.05 (3H, d, J = 3.8 Hz), 3.55 (2H, d, J = 3.8 Hz), 4.30 (2H, q), and 7.25 (5H, m); *m*/*e* 222 (37), 177, 149, 129, and 91; GC purity: ≥99%] together with the phenyl-inserted derivatives **50** and **51** [compound **50**: ^{1}H-NMR ($CDCl_3$) δ 1.12 (3H, t), 2.10 (3H, s), 3.78 (2H, s), 4.20 (2H, q), 7.40 (10H, m); *m*/*e* 280 (73), 234, 206, 191, 155, 129, and 91. Compound **51**: ^{1}H-NMR ($CDCl_3$) δ 1.25 (3H, t), 2.30 (3H, s), 3.55 (2H, s), 4.15 (2H, q), and 7.40 (10H, m); *m*/*e* 280 (23), 234, 206, 189, 156, 115, and 91]. Further elution with pentane containing 5% of ether afforded 0.33 g (24%) of indene **46**: IR ($CHCl_3$) 1705 (CO), 1655 cm^{-1} (C═C); ^{1}H-NMR ($CDCl_3$) δ 1.35 (3H, t), 2.53 (3H, m), 3.60 (2H, m), 4.30 (2H, q), and 7.25 (4H, m); *m*/*e* 202 (33), 157, 143, and 129. Anal. Calcd for $C_{13}H_{14}O_2$: C, 77.20; H, 6.98. Found: C, 77.10; H, 7.00. Following elution with the same solvent yielded an inseparable mixture (0.138 g) of the two indenes **46** and **47** [indene **47**: ^{1}H-NMR ($CDCl_3$) δ 1.25 (3H, t), 2.53 (3H, m), 3.55 (2H, m), 4.20 (2H, q), and 7.35 (4H, m); *m*/*e* 202 (1), 129, 128, and 91]. Further elution with pentane containing 7% of ether gave an inseparable mixture (0.23 g, 15%) of the two β-keto-esters **48** and **49** [NMR **48**: ^{1}H-NMR ($CDCl_3$) δ 1.13 (3H, t), 2.14 (3H, s), 3.09 (1H, d, J = 6.5 Hz), 3.60 (2H, d, J = 8.6 Hz), 4.10 (2H, q, J = 6.5 Hz), and 7.15 (5H, m). NMR **49**: ^{1}H-NMR ($CDCl_3$) δ 1.14 (3H, t), 1.20 (3H, m), 2.05 (1H, m), 3.80 (2H, s), 4.10 (2H, q, J = 6.5 Hz), and 7.15 (5H, m)]. Finally, further elution with pentane containing 10% of ether afforded lactone **52** (0.100 g, 8.4%): ^{1}H-NMR ($CDCl_3$) δ 2.15 (3H, m), 5.05 (2H, m), and 7.50 (5H, m); ^{13}C-NMR (75 MHz, $CDCl_3$) δ 10.4, 70.3, 122.7, 127.1, 129, 130.1, 131.2, 154.8, and 175.3. Anal. Calcd for $C_{11}H_{10}O_2$: C, 75.84; H, 5.79. Found: C, 75.80; H, 5.80.

A solution of 1.00 g (4.03 mmol) of **43** in 10 mL of pentane was added dropwise during 30 min to a magnetically stirred solution of 0.87 mL (6.15 mmol) of freshly distilled BF_3·Et_2O in 10 mL of pentane under nitrogen at 0 °C. Stirring was continued for 10 min after which a saturated sodium hydrogen carbonate solution was added, and the resulting mixture was extracted with ethyl acetate. The combined organic phases were washed with brine and dried over anhydrous sodium sulfate. After evaporation of the solvent, the residue (0.90 g) was submitted to flash chromatography on silica gel using a pentane−ethyl acetate mixture (95:5) to give 0.089 g (10%) of the fluoro derivative **44** followed by a mixture containing **44** and **45** (0.134 g, 15%). Further elution with pentane containing 10% of ethyl acetate afforded indene **46** (0.065 g, 8%). Further elution with the same solvent yielded a mixture containing **46** and **47** (0.212 g, 26%). Further elution with pentane containing 20% of ethyl acetate gave an inseparable mixture of β-ketoesters **48** and **49** (0.058 g, 6.6%). Finally, further elution with pentane containing 30% of ethyl acetate afforded 0.070 g (10%) of lactone **52**.

A solution of 1.00 g (4.03 mmol) of **43** in 10 mL of acetonitrile was added dropwise during 30 min to a magnetically stirred solution of 0.87 mL (6.15 mmol) of freshly distilled BF_3·Et_2O in 10 mL of acetonitrile under nitrogen at 0 °C. Stirring was continued for 10 min after which a saturated sodium hydrogen carbonate solution was added and the resulting mixture was extracted with ethyl acetate. The combined organic phases were washed with brine and dried over anhydrous sodium sulfate. After evaporation of the solvent, the residue (0.90 g) was submitted to flash chromatography on silica gel using a pentane−ethyl acetate mixture (90:10) to give a mixture of indenes **46** and **47** (0.179 g, 22%). Further elution with pentane containing 20% of ethyl acetate gave an inseparable mixture of β-ketoesters **48** and **49** (0.177 g, 20%). Finally, further elution with the same solvent afforded enamide **53** (0.316 g, 30%): ^{1}H-NMR ($CDCl_3$) δ 1.25 (3H, t), 1.95 (3H, s), 2.50 (3H, s), 3.72 (2H, s), 4.20 (2H, q), and 7.30 (5H, m). Anal. Calcd for $C_{15}H_{19}NO_3$: C, 68.94; H, 7.33; N, 5.36. Found: C, 68.90; H, 7.30; N, 5.40.

Reaction of 1-Hydroxy-1-(ethoxycarbonyldiazomethyl)-2,2,6,6-tetradeuterocyclohexane (84) with Boron Trifluoride Etherate. A suspension containing 5.68 g (57.9 mmol) of cyclohexanone and 0.60 g of potassium carbonate in 90 mL of deuterium oxide was heated at reflux for 62 h. After cooling, the reaction mixture was extracted with ether, and the combined organic phase was concentrated under reduced pressure. The residue (6 g) was distilled to give 5.6 g (95%) of 2,2,6,6-tetradeuterated cyclohexanone: bp 154−6 °C; ^{1}H-NMR ($CDCl_3$) δ 1.80 (6H, m).

A cold (−78 °C) solution of lithium diisopropylamide [prepared from the addition of 16.65 mL of a 1.18 M hexane solution of *n*-butyllithium to 2.23 g (22.0 mmol) of a solution of diisopropylamine in 20 mL of THF] was added during 40 min to a stirred solution of 1.76 g (17.2 mmol) of the above tetradeuterated cyclohexanone and 2.04 g (17.9 mmol) of ethyl diazoacetate at −78 °C under a nitrogen atmosphere. After the addition was complete, 1 mL of acetic acid in 20 mL of ether at −78 °C was added, and the reaction mixture was allowed to warm to room temperature. Water was added, the organic phase was separated, and the aqueous layer was extracted with chloroform. The combined organic phase was washed with brine and dried over anhydrous sodium sulfate. After evaporation of the solvent, the residue (4.3 g) was chromatographed on alumina (activity IV) eluting with pentane−ether to give 2.67 g (72%) of **84**: IR ($CHCl_3$) 2045 (C═N_2), 1665 cm^{-1} (CO); ^{1}H-NMR ($CDCl_3$) δ 1.31 (3H, t, J = 7 Hz), 1.43−2.00 (6H, m), 3.60 (1H, m), 4.20 (2H, q, J = 7 Hz).

A solution of 0.88 g (4.07 mmol) of **84** in 8 mL of benzene was added dropwise over a 10 min period to a solution of 0.75 mL (6.1 mmol) of BF_3·OEt_2 in 10 mL of benzene kept under vigorous magnetic stirring at 5 °C under a nitrogen atmosphere. After the addition was complete, the reaction mixture was allowed to warm to room temperature and was then concentrated *in vacuo*. The residue (0.5 g) was submitted to flash silica gel chromatography using a pentane−ether mixture. The major fraction contained 0.35 g (35%) of ethyl 2-phenyldideuteromethyl-6,6-dideuterocyclohexenecarboxylate (**85**): IR ($CHCl_3$) 1695 cm^{-1} (CO); ^{1}H-NMR ($CDCl_3$) δ 1.25 (3H, t, J = 7 Hz), 1.58 (4H, m), 2.02 (2H, m), 4.22 (2H, q, J = 7 Hz), 7.27 (5H, m).

Computational Results. The methyl esters of **64**−**66** were constructed in MacroModel[66] as their neutral hydrides and optimized with the MM2 force field. The appropriate H^- was removed, and the corresponding carbocation was subsequently optimized with the 6-31G* basis set over cartesian coordinates in Gaussian-92.[67] Vinyl cations **64a**−**c** were thus submitted to G-92 with initial θ(C═C$^+$C(CO))'s around 120°. Similarly, the cyclic vinyl cations **65a**−**c** were input to the ab initio calculation with ring geometries very similar to that found in cycloheptene and cyclohexene, respectively. Furthermore, the carbonyl of the ester group was positioned *syn* to the vinyl cation center. Distortion from neutral hydrocarbon geometries as listed in Table 1 are a direct result of the gas phase 6-31G* optimization. Allyl cations **66a**−**c** were treated similarly, the $CH_2$$^+$C═C moiety introduced as a planar fragment and the ester C═O oriented *syn* to the exocyclic CH_2 group.

The simpler structures **67**−**69** were geometry optimized by employing Z-matrix input. Transition states **70**‡ and **71**‡ sustain a single negative eigenvalue after geometric refinement. Structures **79**−**77**‡ carrying a molecule of dimethyl ether (Table 2) were treated similarly. All final refined G-92 structures were subjected to coordinate conversion and viewed in 3-D with Sybyl software.[68]

Acknowledgment. A.P. gratefully acknowledges support of this work by the National Science Foundation. B.L.W. is pleased to acknowledge the NIH for a postdoctoral fellowship (GM-16184-01). Use of the high-field NMR spectrometer used in these studies was made possible through equipment grants from the NIH and NSF.

Supporting Information Available: Tables of 6-31G* relative energies for V_1, V_2, and A_1 with optimized geometries for dimethyl ether solvated carbocations as well as supplemental experimental for the preparation of esters **26**, **35**, **37** and **42** (4 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, can be ordered from the ACS, and can be downloaded from the Internet; see any current masthead page for ordering information and Internet access instructions.

JA950971S

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