

cladditions (just as we believe they exert considerable influence on product regiochemistry^{16a}) and have proposed a set of simple rules to assign facial stereochemistry based on these interactions. Steric effects also appear to be important in some instances, although the proper relative weighting of the two remains to be established. Further efforts to explore this issue as well as the eventual consequences of electrostatic control of reaction regio- and stereochemistry are presently underway in our laboratory.²¹

Note Added in Proof. Fleming and Williams²⁵ have found that

addition of 2,5-di(trimethylsilyl)cyclopentadiene with tetracyanoethylene gives rise to a single product, corresponding to the addition of the dienophile *anti* to the electropositive trimethylsilyl group on the diene. This result, which is in full accord with electrostatic dictates, would also have been reached on the basis of steric arguments.

(25) Fleming, I.; Williams, R. V. *J. Chem. Soc., Perkin Trans. 1* 1981, 684.

Modeling Chemical Reactivity. 6. Comparison of Conformational Energy Profiles and Electrophilic Reactivities and Stereoselectivities of Chiral Allylic Alcohols and Ethers. Evidence against Intramolecular Hydrogen Bonding in Allylic Alcohols

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Abstract: Conformational energy profiles for 3-buten-2-ol and 2-methoxy-3-butene, obtained from a uniform level of nonempirical molecular orbital theory, are qualitatively similar; the differences between the two appear to arise primarily because of steric interactions. The lowest energy conformers for both position the OH (OR) group directly over the double bond, casting doubt on the previously advanced interpretation that the equilibrium conformation of the allylic alcohol is directed in part by hydrogen bonding between the hydroxylic hydrogen and the π bond. It suggests instead that the conformational biases in both the alcohol and ether are influenced primarily by minimization of oxygen lone pair- π bond repulsion. Electrostatic potentials indicate a preference for electrophilic attack *anti* to the OR group in the high-abundance but low-reactivity conformers of 2-methoxy-3-butene and *syn* to OR in the less abundant but much more reactive conformers, the same preferences as have previously been noted in 3-buten-2-ol. Given that electrophilic addition to allylic alcohols and ethers generally occurs *syn* to the OH (OR) functionality, the results of the theory support a notion that the overall reaction stereochemistry in these systems is influenced more by relative conformer reactivity than by relative abundance.

The use of alcohols and their derivatives for asymmetric induction is widespread and well-documented.^{1,2} The entire spectrum of organic reaction types, i.e., oxidation, reduction, electrophilic and nucleophilic additions, and pericyclic processes, may be rendered stereoselective upon judicious incorporation of OR functionality in the substrate. Differences in reactivities of alcohols and their analogous ethers have generally been assumed to be steric in nature,³ substitution at oxygen either effecting a change in the distribution of conformers (in flexible acyclic systems) or acting to "shield" the double bond from an incoming reagent. In fact, very little quantitative data actually exist with which to test such a "steric hypothesis". Only recently have the conformational preferences of a simple chiral alcohol been established experimentally,^{4a} and there is virtually no experimental information regarding changes in the conformational profile of such a system as a result of substitution at oxygen. Because of

the lack of experimental data, and in view of their obvious synthetic importance, we have undertaken a theoretical study to compare and contrast the conformational preferences and inherent reactivity differences of free alcohols with their methyl ether analogues.

Here we examine the conformational energy profiles for a simple chiral allylic alcohol, 3-buten-2-ol, and for its corresponding methyl ether, 2-methoxy-3-butene, as obtained from a uniform level of nonempirical (*ab initio*) molecular orbital theory. These particular systems have been chosen because they function as prototypes for a class of compounds of considerable importance to asymmetric synthesis² and because of the availability of a microwave spectrum for 3-buten-2-ol,^{4a} in which structures and relative energies for the two (presumed) lowest energy conformers have been assigned. These data allow assessment of the performance of the theory.

Both allylic alcohol structures uncovered in the microwave study show the hydroxylic hydrogen proximate to the allylic π system; this has been interpreted as evidence for intramolecular hydrogen bonding.⁴ Were this the primary factor responsible for the conformational preferences in 3-buten-2-ol, it would be expected that the conformational profile for the corresponding methyl ether, where "hydrogen bonding" can no longer occur, would be markedly different. The possibility that allylic alcohols and ethers might exhibit significant differences in equilibrium conformer populations would then provide the basis for explaining differences in their reactivity. Here we compare and contrast the conformational profiles of 2-methoxy-3-butene and its analogous alcohol, 3-buten-2-ol, and in so doing subject the hydrogen-bonding hypothesis to test.

Our second objective is to examine the similarities and differences in the electrophilic reactivities of analogous allylic alcohol

(1) For general reviews of asymmetric synthesis see: (a) Morrison, J. D.; Mosher, H. S. *Asymmetric Organic Reactions*; Prentice Hall: New York, 1971. (b) Bartlett, P. A. *Tetrahedron* 1980, 36, 2. (c) *Asymmetric Synthesis*; Morrison, J. D., Ed.; Academic Press: New York, Vol. 2, 1983; Vol. 3, 1984; Vol. 4, 1985; Vol. 5, 1985.

(2) For several recent applications, see: Tetrahedron. Symposia-in-Print: *Control of Acyclic Stereochemistry*; Mukaiyama, T., Ed. *Tetrahedron* 1984, 40, 2197-2343.

(3) Cha, J. K.; Christ, W. J.; Kishi, Y. *Tetrahedron* 1984, 40, 2247 and references therein.

(4) (a) Smith, Z.; Carballo, N.; Wilson, E. B.; Marstokk, K.-M.; Møllendal, J. *J. Am. Chem. Soc.* 1985, 107, 1951. The microwave spectra of other allylic alcohols have been reported: (b) Murty, A. N.; Curl, R. F., Jr. *J. Chem. Phys.* 1967, 46, 4176. (c) Lum, D. K.; Bauman, L. E.; Malloy, T. B., Jr.; Cook, R. L. *J. Mol. Struct.* 1978, 50, 1. (d) Horn, A.; Marstokk, K.-M.; Møllendal, H.; Priebe, H. *Acta Chem. Scand.* 1983, A37, 679.

Table I. Conformational Energy Differences for 3-Buten-2-ol and 2-Methoxy-3-butene

molecule and conformation	R = H (1) ^a			R = CH ₃ (2)		
	$\omega_{C=CCO}$	ω_{CCOH}	E^b	$\omega_{C=CCO}$	ω_{CCOR}	E^b
a CH eclipsed, OR <i>trans</i> to CH ₃	-130	-58	0.0 (57)	-131	-70	0.0 (81)
b CO eclipsed, OR <i>trans</i> to CH ₃	13	-66	0.6 (21)	-15	-84	1.1 (13)
c CO eclipsed, OR <i>trans</i> to H	-10	67	0.8 (15)	c	c	c
d CO eclipsed, OR <i>trans</i> to vinyl	3	182	1.6 (4)	1	159	2.1 (2)
e CH eclipsed, OR <i>trans</i> to H	-123	60	1.9 (2)	-116	62	4.1 (<1)
f CH eclipsed, OR <i>trans</i> to vinyl	-139	182	2.7 (1)	-139	164	2.1 (2)
g CC eclipsed, OR <i>trans</i> to vinyl	125	175	2.8 ^{c,d}	149	159	3.0 (<1)
h CC eclipsed, OR <i>trans</i> to methyl	122	-61	3.0 ^{c,d}	142	-82	3.3 (<1)

^a From ref 5d. ^b 6-31G*/3-21G, kcal mol⁻¹. Relative equilibrium abundances, given as $e^{-\Delta E/RT}$ for $T = 298$ K, and normalized to 100% total abundance, are provided in parentheses. ^c Not a local minimum. ^d The methyl group has been constrained to be coplanar with the CC double bond.

and ether conformers. Our efforts center around the use of reactivity models, which have recently been developed in our laboratory and successfully applied to the study of the regio- and stereoselectivities in a variety of chemical systems.^{5,6} The models assess relative electrophilic reactivity in terms of the attraction or repulsion of the substrate toward a test reagent. We have already suggested that the stereoselectivity of electrophilic additions to conformationally flexible chiral systems is ultimately dictated by no fewer than three factors—(1) the relative equilibrium abundances of the conformational minima, (2) the relative reactivities of the available forms, and (3) the stereoselectivities of the individual conformers—and further stressed the need to balance these factors in any analysis of overall product stereochemistry. In our previous study with chiral allylic alcohols,^{5b,d} it was found that in order to bring the results of modeling calculations in line with experimental observation, it was necessary to assume that high relative reactivity is more important than high relative abundance.⁷ The present work, with analogous allylic ether conformers, should provide additional evidence with which to test such an interpretation and, more generally, should assist in the development of predictive rules as aids for the design of new regio- and stereoselective methodologies.

Computational Methods

All calculations have been carried out at the single-determinant (Hartree-Fock) level. Optimum geometries for all conformational minima have been obtained at the 3-21G level,⁸ subject only to the constraint that the incorporated olefin maintain a planar skeleton.⁹ These are provided in an appendix to this paper. Single-point calculations have then been performed with use of the 6-31G* polarization basis set¹⁰ in order to provide better estimates of conformational energy differences. All ab initio calculations have been performed with the GAUSSIAN 85 program system¹¹ as implemented on a Harris H800 digital computer.

Electrostatic potentials have been obtained at the 3-21G level, according to methods described earlier.^{5a,6a} These have been superimposed onto electron-density surfaces corresponding to $\psi^2 = 0.002$ e/bohr^{3,12}

Conformational Analysis of 2-Methoxy-3-butene. Comparison with 3-Buten-2-ol

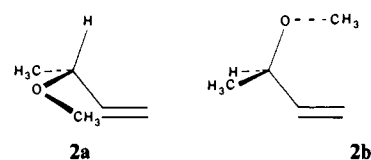
Seven minima have been located on the 3-21G energy surface for 2-methoxy-3-butene (2). Relative energies, obtained at the

Table II. Comparison of Calculated and Experimental Equilibrium Geometries for Lowest Energy Conformers of 3-Buten-2-ol

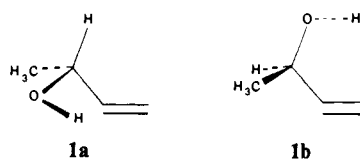
conformer	geometrical parameter	calcd ^{a,b}	expt ^{b,c}
1a	$\angle(C=CC)$	125	127
	$\angle(CCC)$	112	110
	$\omega(C=CCO)$	-130	-122
	$\omega(CCOH)$	-58	-53
1b	$\angle(C=CC)$	123	127
	$\angle(CCC)$	111	112
	$\omega(C=CCO)$	13	4
	$\omega(CCOH)$	-66	-70

^a Theoretical data from ref 5d. ^b Bond angles and dihedral angles in degrees. ^c Experimental data from ref 4a. Only the parameters listed were actually determined on the basis of assumed values for the remaining parameters.

6-31G*/3-21G level, provided in Table I, are compared to previously reported theoretical data for the analogous alcohol, 3-buten-2-ol (1).^{5d,13} Calculated dihedral angles ($\omega_{C=CCO}$ and ω_{CCOR}) are also supplied, quantifying the conformational assignments. The two most stable conformers of the allylic ether, **2a** and **2b**, have the methoxy group positioned directly over the double bond.



Structure **2a** has the allylic hydrogen (approximately) in the plane of the double bond, while in **2b** the CO linkage eclipses C=C. These two structures are, in fact, closely analogous to the two lowest energy forms for 3-buten-2-ol, **1a** and **1b**.^{5d,13} Detailed



comparison of the CCCO and CCOH (CCOC) dihedral angles (Table I) shows how similar the two sets of structures really are.

Experimental structural data on 2-methoxy-3-butene are presently unavailable with which to assess the performance of the theory. Some experimental structural information does exist on the two most stable conformers of the analogous alcohol, 3-buten-2-ol,^{4a} and is compared to the corresponding calculated quantities^{5d} in Table II. The agreement between the two sets of data is moderately good, especially in view of the fact that the relatively few experimental structural parameters actually determined are based on assumed values for all bond lengths and most bond angles. In particular, calculated skeletal dihedral angles are within a few degrees of the assigned experimental values.

No form analogous to structure **1c**, the third "hydrogen-bonded" conformer in 3-buten-2-ol, appears on the conformational energy

(5) (a) Kahn, S. D.; Pau, C. F.; Overman, L. E.; Hehre, W. J. *J. Am. Chem. Soc.* **1986**, *108*, 7381. (b) Kahn, S. D.; Pau, C. F.; Hehre, W. J. *Ibid.* **1986**, *108*, 7396. (c) Kahn, S. D.; Hehre, W. J. *Ibid.* **1986**, *108*, 7399. (d) Part 4: Kahn, S. D.; Pau, C. F.; Hehre, W. J. *Ibid.*, in this issue. (e) Part 7: Kahn, S. D.; Pau, C. F.; Chamberlin, A. R.; Hehre, W. J. *Ibid.*, in this issue.

(6) (a) Pau, C. F.; Hehre, W. J., *J. Comput. Chem.*, submitted. (b) Hehre, W. J.; Pau, C. F.; Hout, R. F., Jr.; Francl, M. M. *Molecular Modeling. Computer-Aided Descriptions of Molecular Structure and Activity*; Wiley: New York, 1987.

(7) (a) Curtin, D. Y. *Rec. Chem. Prog.* **1954**, *15*, 111. (b) Seeman, J. I. *Chem. Rev.* **1983**, *83*, 83.

(8) Binkley, J. S.; Pople, J. A.; Hehre, W. J. *J. Am. Chem. Soc.* **1980**, *102*, 939.

(9) Only a slight deviation from planarity might be expected for the systems studied. For a discussion of the significance of olefin pyramidalization, see: Houk, K. N. *Methods Stereochem. Anal.* **1983**, *3*, 1.

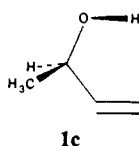
(10) Hariharan, P. C.; Pople, J. A. *Chem. Phys. Lett.* **1972**, *66*, 217.

(11) Hout, R. F., Jr.; Francl, M. M.; Kahn, S. D.; Dobbs, K. D.; McGrath, M. P.; Blurock, E. S.; Pietro, W. J.; Steckler, R.; Hehre, W. J. *Quantum Chemistry Program Exchange*; Indiana University: Bloomington, IN, to be submitted.

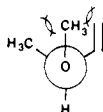
(12) Francl, M. M.; Hout, R. F., Jr.; Hehre, W. J. *J. Am. Chem. Soc.* **1984**, *106*, 563.

(13) Kahn, S. D.; Hehre, W. J. *Tetrahedron Lett.* **1985**, *26*, 3647.

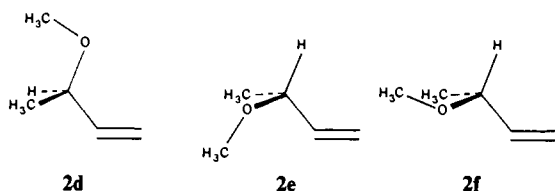
surface for 2-methoxy-3-butene.



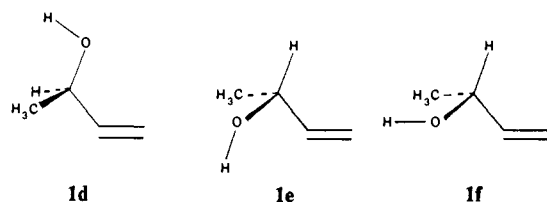
This is probably due to severe steric crowding caused by staggering the ether methyl groups between the allylic methyl group and the olefin skeleton, i.e.,



Three of the five remaining conformational minima located for 2-methoxy-3-butene, **2d-f**,

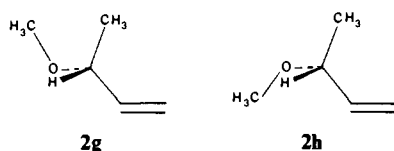


again closely match up with structures **1d-f** in the analogous alcohol.



The energy of the best of these three ether structures, **2d**, is 2.1 kcal mol⁻¹ above that of the ground-state conformer, **2a**. This is to be compared with a difference of 1.6 kcal mol⁻¹ for the corresponding alcohol conformers. This increase in conformer energy difference is consistent with the ability of a methyl group to act as an electron donor, and it suggests that unfavorable lone pair- π bond repulsion dictates overall conformational preference in these systems. The high relative energy of **2e** (as compared to **1e**) is no doubt evidence of steric crowding between the two methyl groups.

We interpret the existence of the two conformers, **2g** and **2h**, in which the allylic methyl group is approximately 15–20° out of the olefin plane, as indicative both of the increased importance of lone pair- π bond repulsion in the ether relative to the alcohol and of steric crowding between the ether methyl group and the allylic methyl and vinyl groups.



Such forms do not correspond to potential minima on the conformational profile for 3-buten-2-ol. Note, however, that the energy separation between the artificially constrained structures, **1g** and **1h**, is nearly the same as the gap between **2g** and **2h**.

In summary, there is striking similarity between the calculated conformational profiles of 3-buten-2-ol and 2-methoxy-3-butene, both insofar as assignment of ground-state structure and (qualitatively) with regard to the relative stabilities of the higher energy forms. The high level of agreement between the experimental and theoretical assignments for the two most stable conformers of the alcohol lends credence to the predictions of the calculations with regard to the remaining alcohol conformers, as well as for the energy surface for the corresponding ether. The differences which exist between the conformational energy profiles for the

Table III. Average Electrostatic Potentials for Conformers of 3-Buten-2-ol and 2-Methoxy-3-butene^a

conformation	face	R = H ^b		R = CH ₃	
		C _{α}	C _{β}	C _{α}	C _{β}
<i>a</i>	CH ₃ up	-10.0	-12.0	-10.7	-12.0
	OR up	3.4	-8.8	-7.9	-11.5
<i>b</i>	CH ₃ up	-12.8	-17.6	-14.9	-18.8
	H up	-4.3	-9.6	-8.2	-13.0
<i>c</i>	H up	-12.8	-18.4		
	CH ₃ up	-3.9	-9.2		
<i>d</i>	H up	-16.4	-23.0	-16.2	-21.0
	CH ₃ up	-16.3	-20.4	-17.4	-22.1
<i>e</i>	OR up	-22.0	-17.8	-22.4	-18.7
	CH ₃ up	-7.4	-10.9	-8.8	-11.8
<i>f</i>	OR up	-27.4	-20.5	-26.5	-20.4
	CH ₃ up	-11.1	-13.8	-12.2	-12.5
<i>g</i>	OR up	-32.8	-21.8	-23.0	-18.8
	H up	-8.7	-13.6	-7.9	-13.7
<i>h</i>	OR up	-20.5	-16.8	-24.0	-19.9
	H up	-7.0	-11.4	-10.6	-15.4

^akcal mol⁻¹. 3-21G//3-21G. ^bFrom ref 5d.

two systems are subtle and appear to be due both to steric crowding and to the increased electron density of oxygen due to the electron-donating ability of methyl.

The data on 3-buten-2-ol and 2-methoxy-3-butene, specifically, the observation that the two most stable conformers of the allylic ether are closely analogous to the lowest energy forms of the alcohol, strongly refute the role of "hydrogen bonding" in determining conformation in the allylic alcohol. We propose instead that the conformation about the allylic carbon-oxygen bond is selected in order to minimize repulsion between the high-energy lone pairs on oxygen and the allylic π bond.

Comparison of Electrophilic Reactivities of Chiral Allylic Alcohols and Ethers

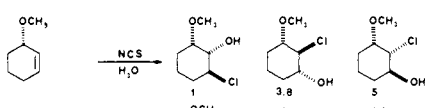
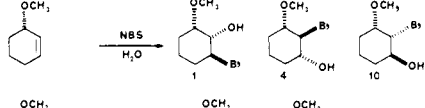
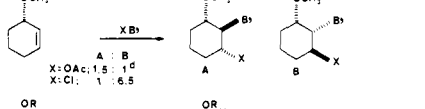
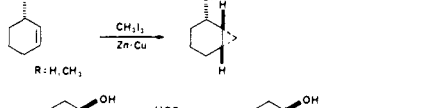
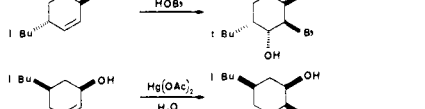
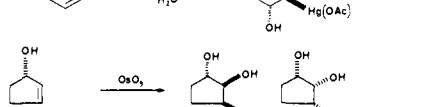
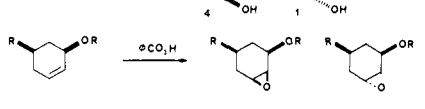
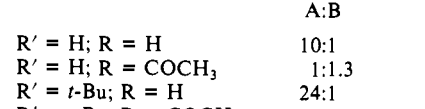
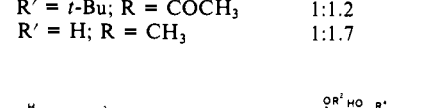
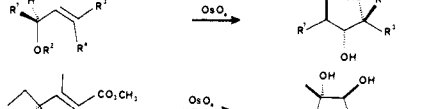
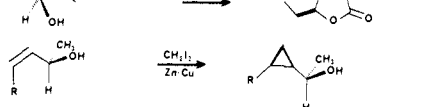

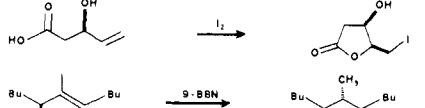
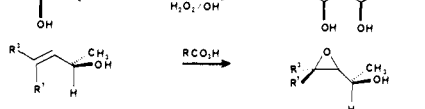
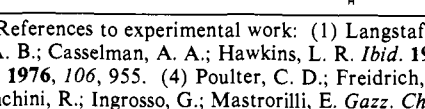
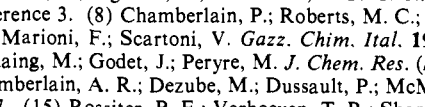
Relative electrophilic reactivities for the diastereotopic faces of the different conformers of chiral allylic alcohols and ethers may be compared in terms of relative electrostatic potentials.¹⁴ As detailed in earlier papers,^{5a,6a} such a model accounts only for Coulombic interactions between the test electrophile (a proton) and the substrate. Effects arising from redistribution of the substrate electron density (polarization), charge transfer from the substrate to the reagent, and nuclear relaxation have not been taken into account. Changes in the electrostatic potential due to charge polarization have previously been investigated and found to be of little importance in describing *relative* electrophilic reactivities.^{5a,d}

Average electrostatic potentials for 3-buten-2-ol (**1**) and its corresponding methyl ether, **2**, are provided in Table III. The data for the alcohol conformers have previously been displayed pictorially.^{5d} The corresponding images for the ether conformers are visually quite similar and will not be presented here.

The data clearly indicate the nearly identical electrophilic reactivity and stereoselectivity of analogous alcohol and ether conformers. Note, in particular, that the low-energy structures **2a** and **2b**, in which the methoxy group is positioned over the π bond, are significantly less reactive than the remaining high-energy conformers, **2d-h**, in which the methyl group on oxygen is far removed. This was also the case for the corresponding alcohol conformers, where the "hydrogen-bonded" structures, **1a-c**, were much less reactive than the alternative geometries, **1d-f**. There are, however, subtle differences between the two sets of data for analogous alcohol and ether conformers, the most interesting of

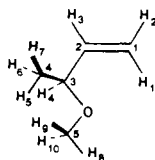
(14) For recent reviews, see: (a) Scrocco, E.; Tomasi, J. *Adv. Quantum Chem.* **1978**, *11*, 115. (b) *Chemical Applications of Atomic and Molecular Electrostatic Potentials*; Politzer, P., Truhlar, D. G., Eds.; Plenum Press: New York, 1981.

Table IV. Summary of Experimental Data for Electrophilic Additions of Chiral Allylic Alcohols and Ethers. Comparison with the Results of the Reactivity Models

reaction	experimental			reactivity models	
	ref ^a	regiochemistry ^b	stereochemistry ^c	regiochemistry ^b	stereochemistry ^c
Conformationally Rigid Systems					
	1	α (major)	<i>syn</i> (major)	α	<i>syn</i>
	2	α (major)	<i>syn</i>	α	<i>syn</i>
	3	α	<i>syn</i> (major)	α	<i>syn</i>
	4		<i>syn</i>		<i>syn</i>
	5	α	<i>syn</i>	α	<i>syn</i>
	6	α	<i>syn</i>	α	<i>syn</i>
	7		<i>anti</i> (major)		<i>e</i>
	8				<i>syn</i>
	9				
		A:B			
		R' = H; R = H	10:1	<i>syn</i> (major)	
		R' = H; R = COCH ₃	1:1.3	<i>anti</i> (major)	<i>e</i>
		R' = <i>t</i> -Bu; R = H	24:1	<i>syn</i> (major)	
		R' = <i>t</i> -Bu; R = COCH ₃	1:1.2	<i>anti</i> (major)	<i>e</i>
		R' = H; R = CH ₃	1:1.7	<i>anti</i> (major)	<i>e</i>
Conformationally Flexible Systems					
	7		CO <i>cis</i> ; H <i>syn</i> CH <i>cis</i> ; OR <i>anti</i>		<i>e</i>
	10		CO <i>cis</i> ; H <i>syn</i> CH <i>cis</i> ; OH <i>anti</i>		<i>e</i>
	11		CH <i>cis</i> ; OH <i>syn</i> CH <i>cis</i> ; H <i>anti</i>		*
	12	α	CH <i>cis</i> ; OH <i>syn</i> CO <i>cis</i> ; H <i>anti</i>	α	*
	13	β	CO <i>cis</i> ; H <i>syn</i> CH <i>cis</i> ; OH <i>anti</i>	β	*
	14	α	CH <i>cis</i> ; OH <i>syn</i> CO <i>cis</i> ; H <i>anti</i>	α	*
	15,16,17		CH <i>cis</i> ; OH <i>syn</i> CO <i>cis</i> ; H <i>anti</i>		*

^aReferences to experimental work: (1) Langstaff, E. J.; Hamanaka, E.; Neville, G. A.; Moir, R. Y. *Can. J. Chem.* **1967**, *45*, 1907. (2) Bannard, R. A. B.; Casselman, A. A.; Hawkins, L. R. *Ibid.* **1965**, *43*, 2398. (3) Bellucci, G.; Berti, G.; Bianchini, R.; Ingrosso, G.; Mastroilli, E. *Gazz. Chim. Ital.* **1976**, *106*, 955. (4) Poulter, C. D.; Freidrich, E. C.; Winstein, S. *J. Am. Chem. Soc.* **1970**, *92*, 6892 and references therein. (5) Gellucci, G.; Bianchini, R.; Ingrosso, G.; Mastroilli, E. *Gazz. Chim. Ital.* **1978**, *108*, 643. (6) Chamberlain, P.; Whitman, G. H. *J. Chem. Soc. B* **1970**, 1382. (7) Reference 3. (8) Chamberlain, P.; Roberts, M. C.; Whitman, G. H. *J. Chem. Soc. B* **1970**, 1374. (9) Barili, P. L.; Bellucci, G.; Berti, G.; Golfarini, M.; Marioni, F.; Scartoni, V. *Gazz. Chim. Ital.* **1974**, *104*, 107. (10) Stork, G.; Kahn, M. *Tetrahedron Lett.* **1983**, *24*, 3951. (11) Raiter, M.; Castaing, M.; Godet, J.; Peryre, M. *J. Chem. Res. (S)* **1978**, 179. (12) Chamberlain, A. R.; Mulholland, R. L., Jr. *Tetrahedron* **1984**, *40*, 2297. (13) Chamberlain, A. R.; Dezube, M.; Dussault, P.; McMills, M. C. *J. Am. Chem. Soc.* **1983**, *105*, 5819. (14) Still, W. C.; Barriss, J. C. *Ibid.* **1983**, *105*, 2467. (15) Rossiter, B. E.; Verhoeven, T. R.; Sharpless, K. B. *Tetrahedron Lett.* **1979**, 4733. (16) Chantemps, P.; Pierre, J.-L. *Tetrahedron* **1976**, *32*, 549. (17) Tanaka, S.; Yamamoto, H.; Nozaki, H.; Sharpless, K. B.; Michaelson, R. C.; Cutting, J. D. *J. Am. Chem. Soc.* **1974**, *96*, 5254.

^bPosition of attachment of electrophile with respect to the directing group. ^cDiastereotopic face attacked. ^dThe addition of BrOAc appears to be anomalous. ^eSee text for discussion.

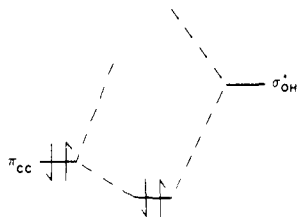
Table V. Structure Data for 2-Methoxy-3-butene Optimized at 3-21G^{a,b}

2a; Energy = -268.49177					
<i>A</i> = 1.315;	<i>B</i> = 1.507;	<i>C</i> = 1.530;	<i>D</i> = 1.442;	<i>E</i> = 1.436;	<i>F</i> = 1.075;
<i>G</i> = 1.073;	<i>H</i> = 1.076;	<i>I</i> = 1.086;	<i>J</i> = 1.082;	<i>K</i> = 1.083;	<i>L</i> = 1.083;
<i>M</i> = 1.080;	<i>N</i> = 1.083;	<i>O</i> = 1.086;	<i>a</i> = 124.7;	<i>b</i> = 111.4;	<i>c</i> = 110.3;
<i>d</i> = 115.3;	<i>e</i> = 121.8;	<i>f</i> = 122.0;	<i>g</i> = 120.9;	<i>h</i> = 109.8;	<i>i</i> = 109.5;
<i>j</i> = 110.7;	<i>k</i> = 109.2;	<i>l</i> = 106.6;	<i>m</i> = 111.7;	<i>n</i> = 111.2;	<i>o</i> = -131.0;
<i>p</i> = -116.2;	<i>q</i> = 121.5;	<i>r</i> = 177.6;	<i>s</i> = 121.0;	<i>t</i> = -118.6;	<i>u</i> = 70.1;
<i>v</i> = 179.7;	<i>w</i> = 119.5;	<i>x</i> = -119.0			
2b; Energy = -268.49209					
<i>A</i> = 1.314;	<i>B</i> = 1.511;	<i>C</i> = 1.533;	<i>D</i> = 1.438;	<i>E</i> = 1.438;	<i>F</i> = 1.072;
<i>G</i> = 1.073;	<i>H</i> = 1.076;	<i>I</i> = 1.087;	<i>J</i> = 1.082;	<i>K</i> = 1.084;	<i>L</i> = 1.082;
<i>M</i> = 1.080;	<i>N</i> = 1.083;	<i>Q</i> = 1.085;	<i>a</i> = 123.5;	<i>b</i> = 110.9;	<i>c</i> = 111.7;
<i>d</i> = 115.5;	<i>e</i> = 120.7;	<i>f</i> = 122.0;	<i>g</i> = 121.1;	<i>h</i> = 109.2;	<i>i</i> = 109.9;
<i>j</i> = 110.9;	<i>k</i> = 108.6;	<i>l</i> = 106.5;	<i>m</i> = 111.7;	<i>n</i> = 110.9;	<i>o</i> = 14.5;
<i>p</i> = -117.9;	<i>q</i> = 121.6;	<i>r</i> = -178.9;	<i>s</i> = 121.1;	<i>t</i> = -118.9;	<i>u</i> = 83.8;
<i>v</i> = 179.6;	<i>w</i> = 119.4;	<i>x</i> = -118.9			
2d; Energy = -268.49046					
<i>A</i> = 1.313;	<i>B</i> = 1.508;	<i>C</i> = 1.537;	<i>D</i> = 1.437;	<i>E</i> = 1.434;	<i>F</i> = 1.070;
<i>G</i> = 1.073;	<i>H</i> = 1.076;	<i>I</i> = 1.088;	<i>J</i> = 1.084;	<i>K</i> = 1.084;	<i>L</i> = 1.082;
<i>M</i> = 1.080;	<i>N</i> = 1.084;	<i>O</i> = 1.086;	<i>a</i> = 123.9;	<i>b</i> = 110.6;	<i>c</i> = 108.0;
<i>d</i> = 116.4;	<i>e</i> = 120.7;	<i>f</i> = 121.6;	<i>g</i> = 121.2;	<i>h</i> = 110.4;	<i>i</i> = 111.4;
<i>j</i> = 108.7;	<i>k</i> = 108.9;	<i>l</i> = 106.5;	<i>m</i> = 112.0;	<i>n</i> = 111.3;	<i>o</i> = -0.6;
<i>p</i> = 121.0;	<i>q</i> = -118.9;	<i>r</i> = 176.6;	<i>s</i> = 120.3;	<i>t</i> = -119.7;	<i>u</i> = -159.0;
<i>v</i> = 173.8;	<i>w</i> = 119.2;	<i>x</i> = -118.8			
2e; Energy = -268.48543					
<i>A</i> = 1.315;	<i>B</i> = 1.511;	<i>C</i> = 1.537;	<i>D</i> = 1.445;	<i>E</i> = 1.434;	<i>F</i> = 1.075;
<i>G</i> = 1.073;	<i>H</i> = 1.075;	<i>I</i> = 1.080;	<i>J</i> = 1.083;	<i>K</i> = 1.083;	<i>L</i> = 1.084;
<i>M</i> = 1.080;	<i>N</i> = 1.084;	<i>O</i> = 1.083;	<i>a</i> = 123.9;	<i>b</i> = 110.8;	<i>c</i> = 112.8;
<i>d</i> = 118.3;	<i>e</i> = 121.9;	<i>f</i> = 121.9;	<i>g</i> = 119.7;	<i>h</i> = 109.0;	<i>i</i> = 109.7;
<i>j</i> = 109.5;	<i>k</i> = 111.7;	<i>l</i> = 105.9;	<i>m</i> = 112.3;	<i>n</i> = 112.1;	<i>o</i> = -115.7;
<i>p</i> = -126.0;	<i>q</i> = 114.1;	<i>r</i> = 173.9;	<i>s</i> = 119.7;	<i>t</i> = -120.7;	<i>u</i> = -61.8;
<i>v</i> = -178.0;	<i>w</i> = 118.6;	<i>x</i> = -118.4			
2f; Energy = -268.48827					
<i>A</i> = 1.314;	<i>B</i> = 1.505;	<i>C</i> = 1.536;	<i>D</i> = 1.444;	<i>E</i> = 1.434;	<i>F</i> = 1.075;
<i>G</i> = 1.073;	<i>H</i> = 1.074;	<i>I</i> = 1.086;	<i>J</i> = 1.084;	<i>K</i> = 1.083;	<i>L</i> = 1.083;
<i>M</i> = 1.079;	<i>N</i> = 1.086;	<i>O</i> = 1.084;	<i>a</i> = 124.7;	<i>b</i> = 110.8;	<i>c</i> = 105.3;
<i>d</i> = 116.2;	<i>e</i> = 122.1;	<i>f</i> = 121.7;	<i>g</i> = 121.5;	<i>h</i> = 110.2;	<i>i</i> = 111.7;
<i>j</i> = 109.9;	<i>k</i> = 109.1;	<i>l</i> = 106.6;	<i>m</i> = 111.2;	<i>n</i> = 112.2;	<i>o</i> = -138.8;
<i>p</i> = -119.6;	<i>q</i> = 118.4;	<i>r</i> = -177.4;	<i>s</i> = 120.2;	<i>t</i> = -120.2;	<i>u</i> = 164.0;
<i>v</i> = -172.6;	<i>w</i> = 118.7;	<i>x</i> = -119.4			
2g; Energy = -268.48593					
<i>A</i> = 1.315;	<i>B</i> = 1.513;	<i>C</i> = 1.528;	<i>D</i> = 1.447;	<i>E</i> = 1.434;	<i>F</i> = 1.073;
<i>G</i> = 1.073;	<i>H</i> = 1.075;	<i>I</i> = 1.088;	<i>J</i> = 1.082;	<i>K</i> = 1.082;	<i>L</i> = 1.082;
<i>M</i> = 1.080;	<i>N</i> = 1.084;	<i>Q</i> = 1.086;	<i>a</i> = 126.3;	<i>b</i> = 114.4;	<i>c</i> = 109.5;
<i>d</i> = 116.2;	<i>e</i> = 123.0;	<i>f</i> = 121.1;	<i>g</i> = 119.1;	<i>h</i> = 109.1;	<i>i</i> = 108.4;
<i>j</i> = 111.6;	<i>k</i> = 109.5;	<i>l</i> = 106.5;	<i>m</i> = 112.4;	<i>n</i> = 111.2;	<i>o</i> = 142.4;
<i>p</i> = -118.0;	<i>q</i> = 119.0;	<i>r</i> = 174.1;	<i>s</i> = 120.1;	<i>t</i> = -118.3;	<i>u</i> = 82.0;
<i>v</i> = 172.9;	<i>w</i> = 119.4;	<i>x</i> = -118.7			
2h; Energy = -268.48656					
<i>A</i> = 1.315;	<i>B</i> = 1.511;	<i>C</i> = 1.531;	<i>D</i> = 1.446;	<i>E</i> = 1.433;	<i>F</i> = 1.073;
<i>G</i> = 1.073;	<i>H</i> = 1.074;	<i>I</i> = 1.088;	<i>J</i> = 1.083;	<i>K</i> = 1.082;	<i>L</i> = 1.082;
<i>M</i> = 1.080;	<i>N</i> = 1.086;	<i>O</i> = 1.084;	<i>a</i> = 126.8;	<i>b</i> = 114.1;	<i>c</i> = 104.6;
<i>d</i> = 116.2;	<i>e</i> = 123.0;	<i>f</i> = 121.0;	<i>g</i> = 120.6;	<i>h</i> = 108.8;	<i>i</i> = 110.8;
<i>j</i> = 110.9;	<i>k</i> = 109.1;	<i>l</i> = 106.5;	<i>m</i> = 111.3;	<i>n</i> = 112.2;	<i>o</i> = 148.8;
<i>p</i> = -121.2;	<i>q</i> = 116.1;	<i>r</i> = 178.7;	<i>s</i> = 119.7;	<i>t</i> = -119.9;	<i>u</i> = 158.7;
<i>v</i> = -174.2;	<i>w</i> = 118.9;	<i>x</i> = -119.1			

^a Energies in hartrees. ^b Bond lengths in angstroms: *A* = C₁C₂; *B* = C₂C₃; *C* = C₃C₄; *D* = C₃O; *E* = OC₅; *F* = C₁H₁; *G* = C₁C₂; *H* = C₂H₃; *I* = C₃H₄; *J* = C₄H₅; *k* = C₄H₆; *L* = C₄H₇; *M* = C₃H₈; *N* = C₃H₉; *O* = C₃H₁₀. Bond angles in degrees: *a* = C₁C₂C₃; *b* = C₂C₃C₄; *c* = C₂C₃O; *d* = C₃OC₅; *e* = C₂C₁H₁; *f* = C₂C₁H₂; *g* = C₁C₂H₃; *h* = C₂C₃H₄; *i* = C₃C₄H₅; *j* = C₃C₄H₆; *k* = C₃C₄H₇; *l* = OC₅H₈; *m* = OC₅H₉; *n* = OC₅H₁₀. Dihedral angles in degrees: *o* = C₁C₂C₃O; *p* = C₄C₃C₂O; *q* = H₄C₃C₂O; *r* = H₅C₄C₃C₂; *s* = H₅C₄C₃H₆; *t* = H₅C₄C₃H₇; *u* = C₂C₃OC₅; *v* = C₃OC₅H₈; *w* = H₈C₅OH₉; *x* = H₈C₅OH₁₀.

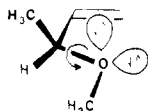
which (at least in the present context) concern the low-energy forms. It was previously shown that all three low-energy conformers of 3-buten-2-ol (**1c-c**) exhibited very low electrophilic reactivity onto the olefin face "shielded" by the hydroxylic hy-

drogen.^{5d} This, it might be argued, is due to favorable interaction between the allylic π bond and σ^*_{OH} , which results in a lowering of the energy of the former and hence reduced electrophilic activity.



In effect, this would be a consequence of "hydrogen bonding". Alternatively, the noted reduction in electrophilic activity could be ascribed to electrostatic repulsion between the electrophile (a proton) and the positively charged hydroxylic hydrogen. The present data strongly support the latter interpretation. The lowering of the energy of the π orbital by "hydrogen bonding" in **1a** to **1c** should result in deactivation of *both* olefin faces toward electrophilic attack. Consequently, replacement of the hydroxylic hydrogen by a methyl group, thereby eliminating the possibility of hydrogen bonding, would be expected to lead to enhanced electrophilic reactivity for *both* faces. The electrostatic potentials provided in Table III clearly indicate that this is not the case, and they show instead that only the olefin face *anti* to the OR functionality is sensitive to replacement. This is, of course, consistent with oxygen lone pair- π bond repulsion as the rationale for the observed conformational biases and with the aforementioned "shielding" as the primary cause of facial deactivation.

The other (more subtle) differences between the electrostatic potentials for the analogous alcohol and ether conformers may be conveniently rationalized in terms of the small geometrical changes previously discussed. This is well-illustrated by contrasting the diastereofacial reactivities of **1d** and **2d**, each of which has the CO bond approximately coplanar with the olefin. The small facial preference for addition of electrophiles *syn* to the allylic hydrogen (*anti* to methyl) in **1d** has previously been interpreted as evidence that a CH bond is better able to stabilize a nascent positive charge, i.e., by hyperconjugation, than a CC linkage,^{5d,15} rather than a commentary on the relative steric crowding afforded an incoming electrophile. Relative electrostatic potentials, which are based on a proton as a model electrophile, are inappropriate for quantitative assessment of possible steric effects. Note that the facial preference in the analogous ether conformer, **2d**, is for attack *syn* to the allylic methyl group. This change from the alcohol may be rationalized in terms of the subtle conformational differences previously noted for the two systems. Steric crowding in **2d** acts to skew the ether methyl group away from the allylic methyl group (and toward the allylic hydrogen). The oxygen lone pairs are thus forced to the side of methyl, i.e.,



causing the noted preference for electrophilic addition.

(15) The relative importance of CH and CC hyperconjugation has not been clearly resolved in the literature. For a recent discussion, see: Sunko, D. E.; Hehre, W. J. *Prog. Phys. Org. Chem.* **1983**, *14*, 205 and references therein.

Concluding Discussion

As discussed earlier, the elucidation of stereoselectivity in acyclic, allyl ethers that a balance be struck between equilibrium abundance and inherent conformer reactivity. In light of our previous efforts with the allylic alcohol system,^{5b,d} the present results on the analogous methyl ether provide the basis for generalizations regarding differences between the two systems.

Inspection of the representative experimental data (Table IV) in which the allyl ether is incorporated into a rigid ring system reveals preferential addition of electrophiles *syn* to oxygen and to the α carbon in those cases where regioselectivity is discernable. This is in complete accord with the reactivity models. Conformers **2g-h**, in which the allylic methyl is approximately 20° out of the olefin plane, adequately model the environment of a cyclohexene ring system.¹⁶ These forms, which are among the most reactive conformers, exhibit large diastereofacial biases for addition of electrophiles *syn* to the directing methoxy group. Such a preference has previously been assumed in constructing interpretations for the observed products in electrophilic additions to cyclohexanols;^{5b,d} it is noteworthy that the present results support the validity of such an assumption. It should also be noted that the nonselective nature of peracid epoxidation of allylic ethers and the opposite stereoselectivity of OsO₄ and permanganate oxidation of allylic alcohols and ethers do not appear to be in accord with the results of the modeling study. The reasons for their deviation are currently under study in our laboratory.¹⁷

The connection between allyl ethers and allyl alcohols is then well-established. Both the conformational preferences and the diastereoselectivity afforded the available forms of 2-methoxy-3-butene correspond closely to those found in 3-buten-2-ol. The prediction of stereoselectivity in additions of electrophiles to chiral, acyclic allyl ethers is therefore expected to follow the same principles governing electrophilic additions to chiral, acyclic allyl alcohols. That is, conformers in which the ether alkyl group is "over" the CC π bond (**2a** and **2b**) will be relatively unimportant in determining the distribution of products due to their greatly attenuated reactivities. Far more influential will be the most reactive conformers, among them, **2d**, which has the allylic hydrogen coplanar with the olefinic double bond. Along with being one of the more abundant forms (2%), this conformer exhibits a marked bias for electrophile addition *syn* and α to the directing ether oxygen. This result is again entirely consistent both with the preferences predicted by the reactivity models for the related allylic alcohols and with the preferences observed experimentally (Table IV).

Appendix. Calculated Equilibrium Structures

Equilibrium structures and energies for 2-methoxy-3-butene conformers, obtained from 3-21G wave functions,⁸ are provided in Table V.

Registry No. 2-Methoxy-3-butene, 17351-24-5; 3-buten-2-ol, 598-32-3.

(16) The thorough investigation of the selectivity in α -substituted cyclohexenes is currently under study in our laboratory.¹⁷

(17) Kahn, S. D.; Hehre, W. J., research in progress.