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The Origin of Diastereofacial Control in Allylboration Reactions Using Tartrate Ester Derived Allylboronates: Attractive Interactions between the Lewis Acid Coordinated Aldehyde Carbonyl Group and an Ester Carbonyl Oxygen

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Abstract: Transition-state structures for the allylboration reaction between the tartrate ester and tartramide modified allylboronates and acetaldehyde are located at the B3LYP/6-31G* level of theory. An attractive interaction between the boron-activated aldehyde and the ester or amide carbonyl oxygen lone pair is found to play a major role in the favored transition states **11a** and **13**. This attractive interaction appears to be electrostatic in origin. However, an $n \rightarrow \pi^*$ charge-transfer type of interaction has not been ruled out. The distance (2.77 Å) between the aldehydic hydrogen and the carbonyl oxygen in transition state **13** is beyond the sum of van der Waals radii. The formyl C−H···O bond angle (109°) in this transition structure deviates far from linearity. Therefore, hydrogen-bonding interactions between the formyl C−H and the amide carbonyl oxygen are considered negligible. The distance (3.81 Å) between the aldehydic oxygen and the amide carbonyl oxygen in the diastereomeric, disfavored transition state **14** is also beyond the van der Waals radii, which suggests that *n*/*n* electronic repulsion plays a lesser role in stereodifferentiation in the allylboration reaction than originally proposed.

Introduction

The allylboration reaction is an important method for synthesis of stereochemically complex, acetate- and propionate-derived acyclic systems.[1,2] Several highly enantioselective auxiliary systems have been introduced for this reaction,[3−13] including the tartrate ester modified allyl- and crotylboronates that first appeared in the literature in 1985.[14−19] It was originally proposed that the origin of asymmetry in the allylation reactions of the tartrate-derived chiral reagents derives from an *n*/*n* electronic repulsive interaction between the nonbonding lone pair on the aldehydic oxygen and the carbonyl oxygen of the tartrate ester, as shown in the disfavored transition state **5**. These interactions are possible only if the dioxaborolane systems of **1**−**3** adopt a conformation in which the two tartate ester units are pseudoaxial and in which the ester carbonyl eclipses the adjacent C−O ether bond, as indicated in transition structures **5** and **6**.

Support for this hypothesis was provided by studies involving the conformationally rigid tartramide-based chiral reagents **4**,[20,21] which exhibit the conformational features assumed for the tartrate ester auxiliary in the favored transition state **6**. Reagents **4** exhibited substantially improved enantioselectivity, typically greater than 95% ee, compared to **1**−**3** (≤88% ee in the best cases). Subsequent X-ray structures of several tartrate ester acetals and NMR studies of tartrate ester-derived 1,3,2-dioxabolanes, verified that the proposed conformation of the tartrate auxiliary is, in fact, favored in ground-state structures.[22] During the course of the latter studies, it was also proposed that the favored allylboration transition state **6** experiences a stabilizing

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(1) Roush, W. R. In *Comprehensive Organic Synthesis*; Trost, B. A., Fleming, I., Eds.; Permagon Press: Oxford, U.K., 1991; Vol. 2.
(2) Chemler, S. R.; Roush, W. R. In *Modern Carbonyl Chemistry*; Otera, J., Ed.; Wiley-VCH: New York, 2000.
(3) Roush, W. R.; Park, J. C. *Tetrahedron Lett.* **1991**, *32*, 6285.
(4) Hoffmann, R. W.; Landmann, B. *Chem. Ber.-Recl.* **1986**, *119*, 1039.
(5) Hoffmann, R. W.; Dresely, S.; Lanz, J. W. *Chem. Ber.* **1988**, *121*, 1501.
(6) Hoffmann, R. W.; Dresely, S. *Chem. Ber.* **1989**, *122*, 903.
(7) Brown, H. C.; Bhat, K. S. *J. Am. Chem. Soc.* **1986**, *108*, 5919.
(8) Brown, H. C.; Bhat, K. S.; Randad, R. S. *J. Org. Chem.* **1987**, *52*, 319.
(9) Brown, H. C.; Bhat, K. S.; Randad, R. S. *J. Org. Chem.* **1989**, *54*, 1570.
(10) Short, R. P.; Masamune, S. *J. Am. Chem. Soc.* **1989**, *111*, 1892.
(11) Garcia, J.; Kim, B.-M.; Masamune, S. *J. Org. Chem.* **1987**, *52*, 4831.
(12) Corey, E. J.; Yu, C. M.; Kim, S. S. *J. Am. Chem. Soc.* **1989**, *111*, 5495.
(13) Brown, H. C.; Randad, R. S.; Bhat, K. S.; Zaidlewicz, M.; Racherla, U. S. *J. Am. Chem. Soc.* **1990**, *112*, 2389.
(14) Roush, W. R.; Walts, A. E.; Hoong, L. K. *J. Am. Chem. Soc.* **1985**, *107*, 8186.
(15) Roush, W. R.; Halterman, R. L. *J. Am. Chem. Soc.* **1986**, *108*, 294.
(16) Roush, W. R.; Palkowitz, A. D.; Palmer, M. J. *J. Org. Chem.* **1987**, *52*, 316.
(17) Roush, W. R.; Ando, K.; Powers, D. B.; Palkowitz, A. D.; Halterman, R. L. *J. Am. Chem. Soc.* **1990**, *112*, 6339.
(18) Roush, W. R.; Palkowitz, A. D.; Ando, K. *J. Am. Chem. Soc.* **1990**, *112*, 6348.
(19) Roush, W. R.; Hoong, L. K.; Palmer, M. A. J.; Straub, J. A.; Palkowitz, A. D. *J. Org. Chem.* **1990**, *55*, 4117.
(20) Roush, W. R.; Banfi, L. *J. Am. Chem. Soc.* **1988**, *110*, 3979.
(21) Roush, W. R.; Grover, P. T. *J. Org. Chem.* **1995**, *60*, 3806.
(22) Roush, W. R.; Ratz, A. M.; Jablonowski, J. A. *J. Org. Chem.* **1992**, *57*, 7, 2047.

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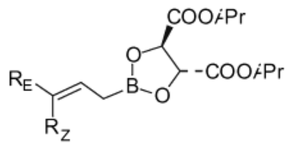
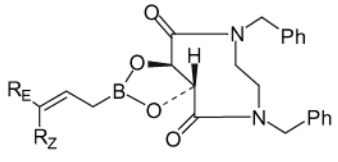
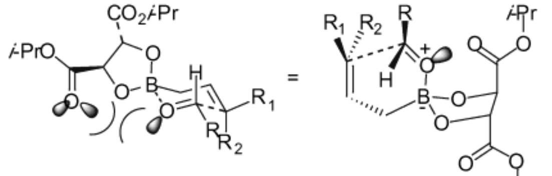


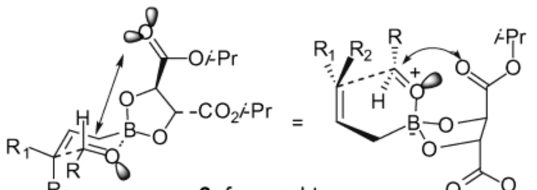
1, $R_E = R_z = H$
2, $R_E = Me$, $R_z = H$
3, $R_E = H$, $R_z = Me$



4



5, disfavored t.s.
n/n repulsive interactions



6, favored t.s.
attractive interactions

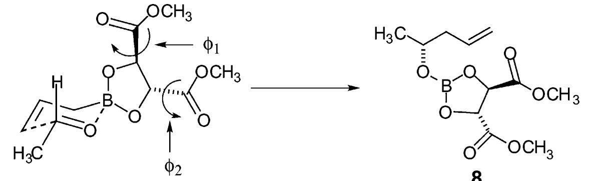
interaction in which the tartrate ester carbonyl group interacts with the aldehyde carbonyl carbon attractively.

Electronic effects such as this are rarely invoked as control elements in diastereoselective reactions. One example was reported by Yamamoto in 1990 for an allylation reaction using an allylstannane reagent.[23] Corey suggested in 1997 that formyl H-bonds could be the control element for a number of diastereoselective reactions involving chiral auxiliaries.[24−27] Formyl hydrogen bonding was also suggested to explain the results of the allylboration reactions of the tartrate ester modified allylboronates **1**−**4**.[24] Despite the differences in the details of these proposals, electronic effects, rather than steric effects, are believed to serve as the origin of stereoselectivity in these reactions. Because the exact nature of the transition state is still unknown and computational studies that take electron-correlation into account[28] for the tartrate ester controlled allylboration reaction have not been performed, we have initiated a density functional study of this fascinating and highly stereoselective reaction.[29−31]

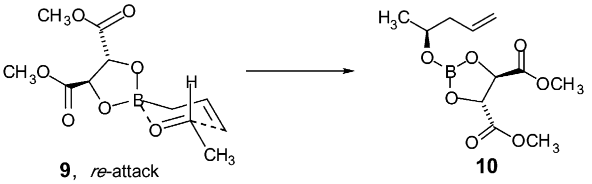
Interest in the origins of diastereofacial selectivity has prompted one of us to use ab initio molecular orbital methods to investigate the transition states of diastereoselective reactions.[32−34] The transition states of the allylboration reactions of reagent **1** with acetaldehyde have 19 heavy atoms, which pushes the limit of computational resources when performed at the B3LYP/6-31G* level of theory. Nevertheless, the transition-state structures for the addition of the tartrate allylboronate **1** and the tartramide-containing reagent **4** to acetaldehyde have been located at the B3LYP/6-31G* level of theory with all key elements of the reactants.[35,36] This study reveals the importance of an attractive interaction between a Lewis acid complexed aldehyde and the lone pairs of the proximate carbonyl group in the transition state. Although this interaction was proposed by one of us in 1992,[22] it is now confirmed by the density functional theory study reported herein.

Computational Methods

Our calculations start from the equilibrium structures of the starting materials and the products. The calculations were carried out using the Gaussian 98 set of programs[37] on the CRAY SV1 supercomputer at the Ohio Supercomputer Center. Initial molecular structures were generated using the Chem3D graphical program. The starting complexes of acetaldehyde and tartrate allylboronate **1** were determined by arrangement according to *si* and *re* π-face attack on the aldehyde. The rotational isomers of the tartrate allylboronate were generated by rotation around the torsional angles, ϕ_1 and ϕ_2 (see eqs 1 and 2) producing three stable conformations for each π-facial attack.



7, *si*-attack **8** (1)



9, *re*-attack **10** (2)

The corresponding conformations of the products were likewise generated by rotating the torsional angles ϕ_1 and ϕ_2. Structural optimizations for the starting materials and products were determined by means of the 3-21G split-valence basis set. The transition-state structures were initially located at the HF/3-21G level of theory, and continued optimization succeeded at the HF/6-31G* and B3LYP/6-31G* levels of theory. The B3LYP/6-31G* method has been found to be adequate for the description of intramolecular hydrogen-bonding interactions.[38] The transition structures have 19 heavy atoms and were fully optimized without any constraints and characterized by vibration

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(23) Yamamoto, Y.; Nemoto, H.; Kikuchi, R.; Komatsu, H.; Suzuki, I. *J. Am. Chem. Soc.* **1990**, *112*, 8598.
(24) Corey, E. J.; Rohde, J. J. *Tetrahedron Lett.* **1997**, *38*, 37.
(25) Corey, E. J.; BarnesSeeman, D.; Lee, T. W. *Tetrahedron Lett.* **1997**, *38*, 4351.
(26) Corey, E. J.; BarnesSeeman, D.; Lee, T. W. *Tetrahedron Lett.* **1997**, *38*, 1699.
(27) Corey, E. J.; Rohde, J. J.; Fischer, A.; Azimioara, M. D. *Tetrahedron Lett.* **1997**, *38*, 33.
(28) Ganguly, B.; Skudlarek, J. W.; Kozlowski, M. C. *Tetrahedron* **2002**, manuscript submitted.
(29) Yi, L.; Houk, K. N. *J. Am. Chem. Soc.* **1989**, *111*, 1236.
(30) Vulpetti, A.; Gardner, M.; Gennari, C.; Bernardi, A.; Goodman, J. M.; Paterson, I. *J. Org. Chem.* **1993**, *58*, 1711.
(31) Gung, B. W.; Xue, X. W. *Tetrahedron: Asymmetry* **2001**, *12*, 2955.
(32) Gung, B. W.; Zhu, Z. H.; Fouch, R. A. *J. Org. Chem.* **1995**, *60*, 2860.
(33) Gung, B. W. *Tetrahedron* **1996**, *52*, 5263.
(34) Gung, B. W. *Chem. Rev.* **1999**, *99*, 1377.
(35) Labanowski, J. K., Andzelm, J. W., Eds. *Density Functional Methods in Chemistry*; Springer: New York, 1991.
(36) Parr, R. G.; Yang, W. T. *Annu. Rev. Phys. Chem.* **1995**, *46*, 701.
(37) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; Montgomery, J. A., Jr.; Stratmann, R. E.; Burant, J. C.; Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Gonzalez, C.; Challacombe, M.; Gill, P. M. W.; Johnson, B. G.; Chen, W.; Wong, M. W.; Andres, J. L.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. *Gaussian 98*, revision A.9; Gaussian, Inc.: Pittsburgh, PA, 1998.

Table 1. Relative Energies (kcal/mol) for Transition States **11**−**14**

structure	basis set			
	HF/6-31G*	B3LYP/6-31G*	B3LYP/6-31G**[a]	MP2/6-31G*[a]
11a	0.0	0.0 (0.0)[b]	0.0	0.0
11b	1.84	1.64 (1.54)[b]	1.48	1.81
11c	2.79	2.37 (2.30)[b]	2.20	2.57
12a	2.0	1.75 (1.61)[b]	1.63	2.45
12b	1.63	1.84 (1.76)[b]	1.86	2.98
12c	2.75	2.47 (2.50)[b]	2.37	3.63
13	0.0	0.0 (0.0)[b]	0.0	0.0
14	2.23	2.14 (1.81)[b]	2.18	3.37

[a] Single-point calculations using the B3LYP/6-31G* structure. [b] Energies including zero-point vibrational energies.

frequency calculations. Only one imaginary frequency was found for each structure. The relative energies of transition states with and without zero-point vibrational energies are tabulated in Table 1. Single-point calculations were performed at the B3LYP/6-31G**//B3LYP/6-31G* and MP2/6-31G* levels. The structures shown in Figures 1 and 2 are calculated at the B3LYP/6-31G* level of theory. To use these electron-correlation models, this study did not take solvent effects into account. No corrections were made on basis-set-superposition errors because all discussions are based on relative energies.[39,40] No attempt was made to give absolute complexation energies or activation barriers.

Results and Discussion

A total of six transition structures were located for the allylboration reaction of tartrate allylboronate **1** and acetaldehyde. Structures **11a**−**11c** are derived from eq 1, i.e., *si* π-facial attack on acetaldehyde, whereas structures **12a**−**12c** represents transition structures from eq 2, the *re* π-facial attack. The transition-state structures from the tartrate diamide allylboronate **4** were also located for each π-facial attack. These structures are shown in Figure 2, presented in two perspective views for each structure.

In practice, the selectivity in the allylboration reactions involving tartrate diamide allylboronate **4** is considerably higher than that of the reactions using tartrate diester allylboronate **1**.[20] This increase in enantioselectivity was proposed to originate from the rigid structure of **4**. The current study shows that the calculated energy difference is greater between the transition-state structures **13** and **14** than between transition-state structures **11a** and **12a** (Table 1). Therefore, the computational results at this level are consistent with the experimental studies. The most favored transition states for the allylboration reactions of tartrate diester allylboronate **1** is **11a** for *si* π-face attack and **12a** for *re* π-face attack. Both ester carbonyl groups nearly eclipse the adjacent dioxaborolane C−O single bonds ($\tau_{O=C-C-O} = 4.5°$) in these preferred transition states. This conformational preference agrees with the normal order of stability for rotational isomers around the torsional angle O═C−C−O,[41] which favors the eclipsed conformation and is consistent with the X-ray structures of the model compounds.[22]

The transition-state structures of reactions of allylboronate **1** with acetaldehyde are shown in Figure 1. An attractive interaction between the ester carbonyl oxygen and the boron-activated aldehyde carbonyl group is present in the most stable transition-state structure for *si* π-face attack (**11a**) as indicated by the short interatomic distance between the ester oxygen atom and the aldehyde carbonyl carbon (3.28 Å). An *n*/*n* repulsive interaction is present in the transition-state structures for *re* π-face attack (**12a**). The interatomic distance between the ester carbonyl oxygen and the aldehyde carbonyl oxygen is 3.26 Å in structure **12a**. These results are consistent with previous predictions.[22] An examination of the transition structures in Figure 2 reveals that the dominant force is the attractive interactions in the favored *si* π-face attack between the amide carbonyl groups and the formally positively charged aldehyde carbonyl group. The dipole of the amide carbonyl group is pointed toward the *re* π-face of the aldehyde, opposite that of the allyl fragment, in the favored transition state **13**. The distance between the amide carbonyl oxygen atom and the aldehydic proton is 2.77 Å. The distance between the amide carbonyl oxygen atom and the aldehyde carbonyl carbon is 3.29 Å, and the amide carbonyl oxygen atom and the aldehyde carbonyl oxygen are separated by 3.33 Å. The attractive interaction can be seen not only from these short distances but also from the bending of the five-membered dioxaborolane ring. The five-membered ring is completely planar in transition structure **14**, whereas it is envelope-shaped with the boron atom out of the plane in structure **13**. This bending of the five-membered ring allows the core six-membered chair transition state to move closer to the amide carbonyl oxygen in **13**. The absence of puckering of the dioxaborolane ring in the stereochemically disfavored transition state **14** contributes to the much greater distances separating the amidic carbonly oxygen from the boron-bound aldehyde: 3.91 Å for the oxygen−oxygen interaction and 4.78 Å for the amide oxygen−aldehyde carbon contact. Also, as shown in Figure 2, the distance between the allylic hydrogen atom and the amide carbonyl group on the other side of the five-member ring is 3.91 Å for **13** and 3.2 Å for **14**, indicating a considerable difference between the two transition states.

In transition state **13**, the aldehyde carbonyl dipole (−C═O→) is pointed down and away from the amide carbonyl dipole. In transition state **14**, the aldehyde carbonyl dipole (−C═O→) is pointed more or less against the amide carbonyl dipole, which should raise the transition-state energy. However, we now think that the difference between transition states **13** and **14** is mainly due to the attractive interaction in **13**, rather than repulsive interactions in **14**. This conclusion is drawn from a comparison between the two disfavored transition structures **12a** and **14** originating from *re* π-face attack. The distance between the amide carbonyl oxygen and the aldehyde carbonyl oxygen in transition state **14** is greater than the corresponding distance in **12a** (3.81 vs 3.26 Å). However, the energy difference between **13** and **14** is greater than the energy difference between **11a** and **12a**, an indication that repulsive interactions are not predominant. We propose that the reason for the greater energy difference between transition state **13** and **14** is because the amide carbonyl oxygen is more resonance-stabilized in the negatively charged form than the corresponding oxygen atom in an ester carbonyl group. It is known that an amide carbonyl group is a better hydrogen-bond acceptor than an ester carbonyl group.[42,43] However we do not consider that hydrogen bonding plays a significant role here. The main attraction we propose is

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(38) For a list of references that report favorable results using the B3LYP/6-31G* method for hydrogen-bonding calculations, see: Gonzalez, L.; Mo, O.; Yanez, M. *J. Org. Chem.* **1999**, *64*, 2314.

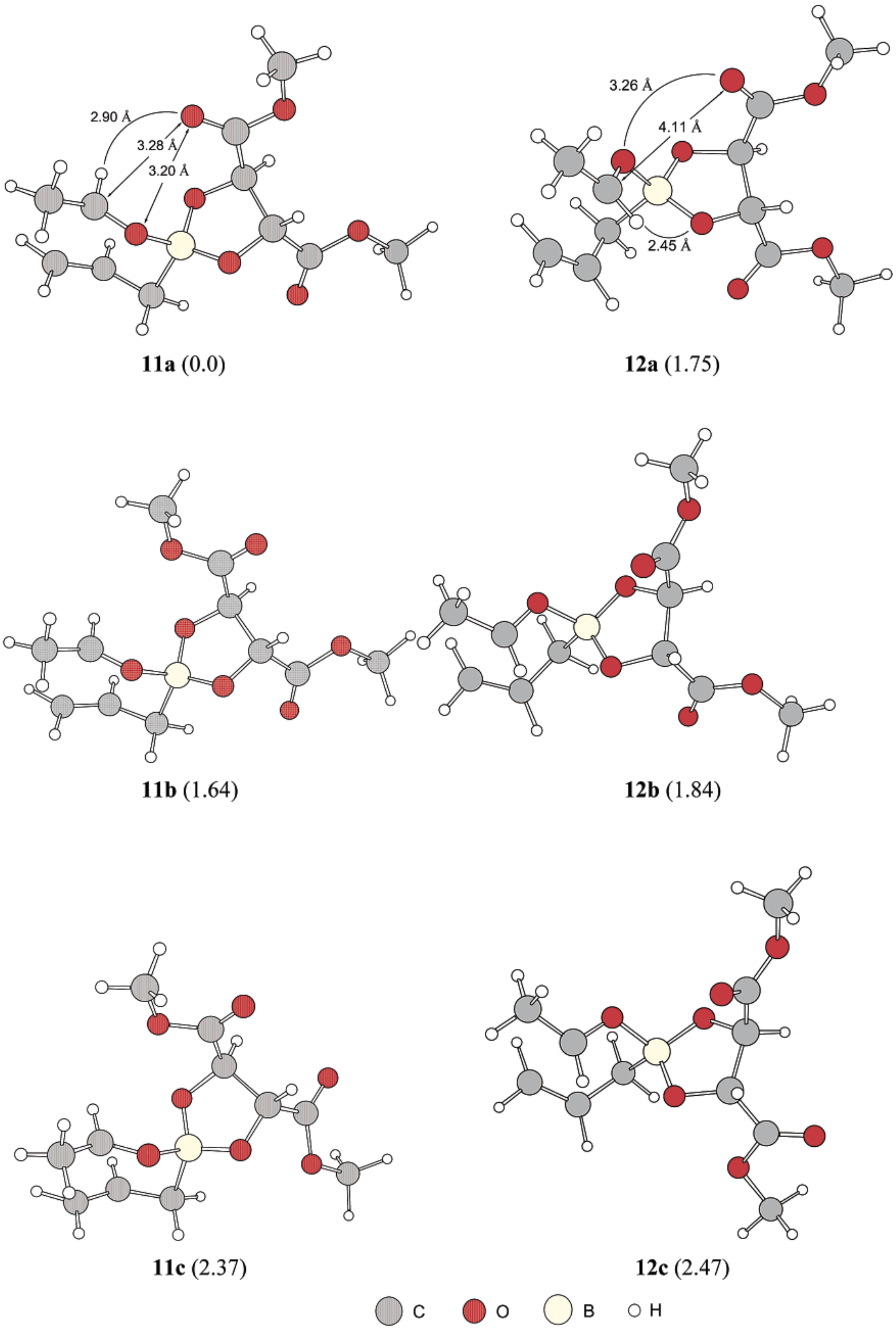
(39) Frisch, M. J.; Delbene, J. E.; Binkley, J. S.; Schaefer, H. F. *J. Chem. Phys.* **1986**, *84*, 2279.

(40) Schwenke, D. W.; Truhlar, D. G. *J. Chem. Phys.* **1985**, *82*, 2418.

(41) Wiberg, K. B.; Laidig, K. E. *J. Am. Chem. Soc.* **1987**, *109*, 5935.

(42) Arnett, E. M.; Mitchell, E. J.; Murty, T. S. *J. Am. Chem. Soc.* **1974**, *96*, 3875.

(43) Gallo, E. A.; Gellman, S. H. *J. Am. Chem. Soc.* **1993**, *115*, 9774.



11a (0.0) **12a** (1.75)

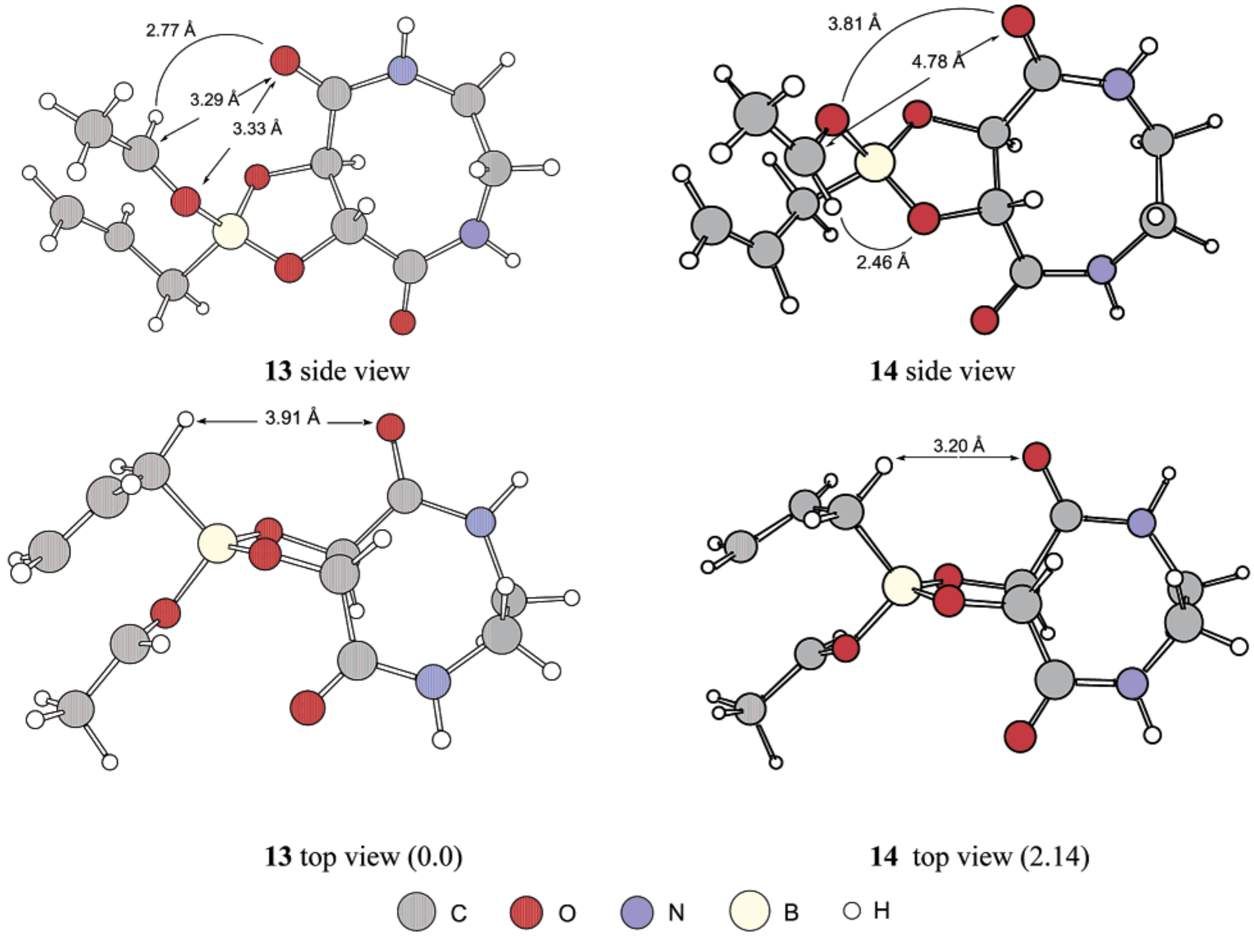
11b (1.64) **12b** (1.84)

11c (2.37) **12c** (2.47)

Figure 1. Transition states **11** and **12** for allylboration of tartrate diester allylboronate **1** with acetaldehyde calculated at the B3LYP/6-31G* level of theory (kcal/mol).

between the amide carbonyl oxygen and the Lewis acid activated aldehyde carbonyl carbon.

Corey has recently reported X-ray crystallographic evidence that suggests the existence of intramolecular formyl C−H hydrogen bonding to oxygen or fluorine ligands in complexes of aldehydes and boron Lewis acids.[24−27,44] The coplanarity of the aldehydic C−H bond and the B−F or B−O bond in the complex places the aldehydic C−H in the proximity of the F


13 side view

14 side view

13 top view (0.0)

14 top view (2.14)

Figure 2. Transition states **13** and **14** for allylboration of tartrate diamide allylboronate **4** with acetaldehyde calculated at the B3LYP/6-31G* level of theory (kcal/mol).

or O atom (2.41−2.59 Å) in a five-membered ring conformation.[44] Corey has used this conformational preference to rationalize the stereoselectivity of a wide range of Lewis acid promoted asymmetric reactions. However, the exact nature and strength of this proposed interaction are still unclear.[45−48] Corey also proposed that a formyl C−H hydrogen bond might occur between the aldehydic proton and the amide carbonyl oxygen in transition structure **13** of the allylboration reactions under consideration here.[24,44] However, the results of our computational study show that the contribution from this formyl H-bond is negligible, if present at all. Two criteria are usually used to judge whether a hydrogen bond is present: (1) the H···B distance (B is the H-bond acceptor; in this case, B = O) and (2) the X−H···B bond angle (X = N, O, or F; in this case, X = C). The distance of a N−H···O hydrogen bond in peptides and proteins is between 1.5 and 2.2 Å.[49] The proposed formyl C−H···O bond in a boron Lewis acid complex has an average length of 2.41−2.59 Å,[44] and H-bonds involving such long distances are considered weak interactions.[49] The formyl C−H···O distance in structures **11a** and **13** are 2.9 and 2.77 Å, respectively, which are beyond the sum of the van der Waals radii of 2.72 Å (H = 1.20 Å and O = 1.52 Å).[50] Therefore, we believe that any stabilizing interactions between the aldehydic C−H and the amide carbonyl oxygen is relatively inconsequential compared to the attractive interaction between the partially positively charged carbonyl carbon and the amide carbony oxygen. Furthermore, a strong hydrogen bond is usually required to have a near-linear X−H···B bond angle.[51] In transition-state structure **13**, the C−H···O angle for this suggested H-bond is 109°, which deviates too far from linearity and should not have a significant bonding interaction given the long distance. Finally, both transition states **13** and **14** contain the five-membered formyl C−H···O bond, but **13** was proposed to have a bifurcated H-bond, which might have a more stabilizing effect.[44] However, the distance between the amide carbonyl oxygen and the aldehydic H is too far in **11a** and **13** to have any significant attraction. In addition a recent study has shown that a bifurcated H-bond in a peptide is energetically less advantageous in solution.[52]

The attractive interaction identified in structure **13** appears to be electrostatic in nature. However, an $n \rightarrow \pi^*$ charge-transfer interaction has not been ruled out.[53,54] A brief survey of the literature reveals a few examples where a similar attractive interaction is present between a Lewis acid complexed carbonyl group and a proximate oxygen lone pair. A preliminary density

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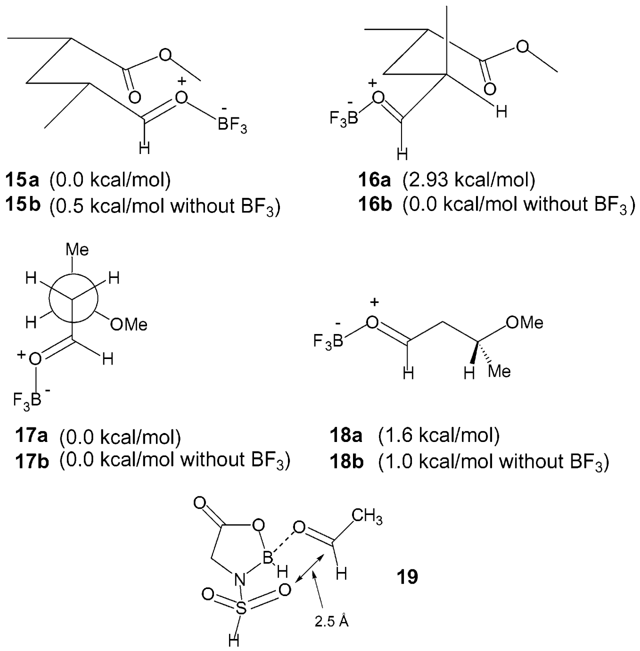
(44) Corey, E. J.; Lee, T. W. *Chem. Commun.* **2001**, 1321.
(45) Salvatella, L.; Ruiz-Lopez, M. F. *J. Am. Chem. Soc.* **1999**, *121*, 10772.
(46) Mackey, M. D.; Goodman, J. M. *Chem. Commun.* **1997**, 2383.
(47) Nevalainen, V. *Tetrahedron: Asymmetry* **1997**, *8*, 2241.
(48) Gung, B. W.; Wolf, M. A. *J. Org. Chem.* **1992**, *57*, 1370.
(49) Jeffrey, G. A. *An Introduction to Hydrogen Bonding*, first ed.; Oxford University Press: New York, 1997.
(50) Bondi, A. *J. Phys. Chem.* **1964**, *68*, 441.
(51) Baker, E. R.; Hubbard, R. E. *Prog. Biophys. Mol. Biol.* **1984**, *44*, 97.
(52) Yang, J. H.; Gellman, S. H. *J. Am. Chem. Soc.* **1998**, *120*, 9090.
(53) Reed, A. E.; Curtiss, L. A.; Weinhold, F. *Chem. Rev.* **1988**, *88*, 899.
(54) Reimann, B.; Buchhold, K.; Vaupel, S.; Brutschy, B.; Havlas, Z.; Spirko, V.; Hobza, P. *J. Phys. Chem. A* **2001**, *105*, 5560.



15a (0.0 kcal/mol)
15b (0.5 kcal/mol without BF_3)

16a (2.93 kcal/mol)
16b (0.0 kcal/mol without BF_3)

17a (0.0 kcal/mol)
17b (0.0 kcal/mol without BF_3)

18a (1.6 kcal/mol)
18b (1.0 kcal/mol without BF_3)

Figure 3. Examples of attractive interactions between Lewis acid complexed aldehyde and oxygen lone pairs. Relative energies are calculated at the B3LYP/6-31G* level of theory.

functional study of Yamamoto's proposal for the preferred conformations of structure **15a** shows that the BF_3-complexed aldehyde **15a** favors the closed conformation (Figure 3).[23] The stretched conformation **16a** is nearly 3 kcal/mol higher in energy. Without the Lewis acid BF_3, the stretched form is slightly favored at the B3LYP/6-31G* level of theory.

Another example can be found in the anti 1,3-asymmetric induction for the addition of allylsilane to BF_3-complexed β-alkoxy aldehydes.[55] The lack of a second coordination site for BF_3 precludes chelation control in this reaction.[56,57] Reetz proposed a polar 1,3-stereoinduction model (**18a**) in which the two oxygen atoms stay far from each other to avoid dipole–dipole repulsion. The attack by allylsilane reagent then occurs from the less hindered side of the stretched structure. In a recent article, Evans suggested a revised 1,3-asymmetric induction model (**17a**) in which the minimization of torsional strain and steric and electrostatic repulsion were emphasized.[58] A possible attractive interaction between the BF_3-complexed aldehyde carbonyl group and the β-alkoxy substituent in the favored transition state was also suggested in Evans' model. Our preliminary calculation shows that the attractive interaction plays a major role here as well (Figure 3).

Another example of an attractive interaction between a Lewis acid activated aldehyde and an oxygen lone pair can be found in a recent theoretical study of the chiral auxiliary N-sulfonyl-1,3,2-oxazaborolidin-5-one (**19**).[45] Among the isomeric complexes found by the investigators, the most stable structure **19** allows an attraction between the sulfonyl oxygen and the aldehyde carbonyl carbon (Figure 3). The authors did not comment on the origin of the order of complex stability. We propose here that the attractive interaction between the sulfonyl oxygen and the boron-activated aldehyde carbonyl carbon is responsible for its stability.

Conclusions

In conclusion, according to density functional theory calculations at the B3LYP/6-31G* level, the favored transition state of the allylboration reactions of the tartrate-derived allylboronate reagents is mainly due to an attractive interaction between the ester or amide carbonyl oxygen and the boron-complexed aldehyde carbonyl group (see transition states **11a** and **13)**. The initially proposed repulsive *n*/*n* lone-pair interaction (see **12a** and **14)** might play a lesser role than previously thought.[14] The formyl C–H···O attractive interaction does not appear to play a significant role in the transition states of this reaction. However, this study does not negate Corey's proposal for application of the formyl C–H···O H-bond concept to the interpretation of other classes of stereoselective reactions. We propose that the attractive interaction between the ester or amide carbonyl oxygen and the Lewis acid activated aldehyde carbonyl group is the main control element in the allylboration reaction of the tartrate ester modified allylboronates. This type of control mechanism has seldom been considered in the comprehension for stereoselective transformations. The results of this study might help in the understanding of experimental facts from diastereoselective reactions. Work along these lines is being actively pursued in our laboratories.

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Supporting Information Available: Internal coordinates of the transition states **11**–**14** including bond lengths, bond angles, and dihedral angles (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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(55) Reetz, M. T.; Kesseler, K.; Jung, A. *Tetrahedron Lett.* **1984**, *25*, 729.
(56) Reetz, M. T. *Angew. Chem., Int. Ed. Engl.* **1984**, *23*, 556.
(57) Reetz, M. T. *Acc. Chem. Res.* **1993**, *26*, 462.
(58) Evans, D. A.; Dart, M. J.; Duffy, J. L.; Yang, M. G. *J. Am. Chem. Soc.* **1996**, *118*, 4322.