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THEORY OF RATES AND STEREOSELECTIVITIES OF CYCLOADDITIONS TO 7-SUBSTITUTED NORBORNADIENES.

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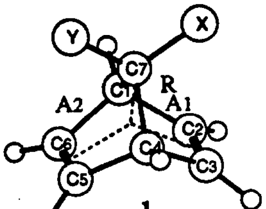
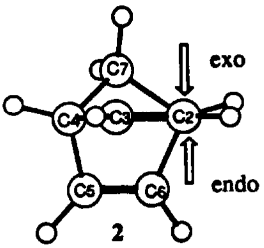
Summary: The structures of 7-substituted norbornadienes have been studied theoretically with the 3-21G basis set. The stereoselectivities and rates of electrophilic cycloadditions of HCCP to these norbornadienes are rationalized.

In the previous communication,[2] we reported examples of stereoselective cycloadditions of hexachlorocyclopentadiene (HCCP) to several 7-substituted norbornadienes, 1. The *exo-anti/endo-anti* ratio is reduced by electron-withdrawing substituents at the 7-position; electron-donating substituents have the opposite effect. Donors increase the overall reaction rate, while acceptors decrease the rate. Partial rate factors indicate that the *exo-anti* addition is very sensitive to the 7-substituent, while the rates of *endo-syn* and *endo-anti* additions are affected only slightly by the substituents. The 7-alkoxyl substituents appear to facilitate the *endo-syn* more than the *endo-anti* attack. Here we offer a general explanation of such phenomena.



1
D_1: $<C_1C_2C_3H$
D_2: $<C_1C_6C_5H$



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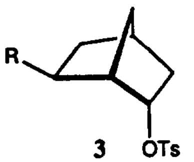

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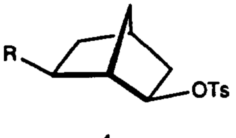

4

The structures of several 7-substituted norbornadienes have been fully optimized with the 3-21G basis set with Pople's GAUSSIAN 86 program.[3] Several key geometrical parameters are given in Table 1. There are small, but systematic, increases in C_1-C_7 bond length R and the average of angles A_1 and A_2 when X changes in the order Cl, F, H, SiH_3. There is pyramidalization at the $C_{sp}2$ centers. The $C_{sp}2$-H bonds in norbornadiene are distorted 2° toward the *endo* direction. This distortion is reduced by electron-withdrawing F and Cl substituents and is increased by the electron-donating SiH_3 substituent.

The C-H distortion in norbornadiene is caused by the unsymmetrical arrangement of the allylic bonds.[4-6] As shown in **2**, which is a Newman projection about C_2-C_1 bond, the C_3-C_2-C_1-C_7 dihedral angle is 36°, and the C_3-C_2-C_1-C_6 dihedral angle is 65°. Such an arrangement is only slightly changed by 7-substituents. The pyramidalization of the olefin occurs *anti*-periplanar to the C_1-C_6 bond to relieve closed-shell repulsion. The variation in the pyramidalization caused by 7-substituents is in accord with this assessment, since an electron-withdrawing substituent reduces the energy of each σ_{C-C} orbital and the π-HOMO, leading to reduced closed-shell repulsion. The opposite effect is caused by electron-donating substituents.

Table 1. Selected geometrical parameters and 3-21G energies of 7-substituted-norbornadienes.

X	Y	R	A_1	A_2	D_1	D_2	E (-a.u.)
H	H	1.566	123.0	123.0	177.8	177.8	268.16187
F	H	1.559	124.2	121.0	178.8	179.2	366.48682
Cl	H	1.552	126.7	119.0	178.9	179.3	724.88274
SiH_3	H	1.573	124.1	122.4	177.5	177.6	556.70742
F	F	1.555	122.6	122.6	179.6	179.6	464.82166

For norbornene and norbornadiene themselves, we have shown that the preference for *exo* attack by all types of reagents, including hexachlorocyclopentadiene, arises from the fact that the *exo* transition state involves partial formation of bonds which are staggered with respect to the allylic bonds on the rigid bicyclic framework.[4-6] Attack from the *endo* direction is accompanied by significant eclipsing of partially formed bonds, with the same allylic bonds as shown in **2**. Such torsional effects in transition states have the same origin as the olefinic pyramidalization in the ground state molecule.[7-8]

Similar arguments explain the variation of the ratio of *exo-anti* to *endo-anti* addition caused by the 7-substituents. A decrease in the pyramidalization caused by 7-electron-withdrawing substituents correlates with a reduced *exo/endo* reaction ratio. This can be understood with torsional strain arguments.[5] The transition state of *endo* attack is destabilized by closed-shell repulsive interactions due to partial eclipsing, and this interaction is reduced by electron-withdrawing substituents and increased by electron-donating substituents.

Simple theoretical models supply support for this argument. The difference in energy between staggered and eclipsed conformations of propane is 3.4 kcal/mol,[9] and reduces to 2.4-2.9 kcal/mol for CH_3-CH_2-CH_2-X, where X is F, Cl, Br, and I.[10] *Ab initio* calculations using the 4-31G basis set and standard geometries give similar results. A Morokuma energy decomposition[11] shows that most of the difference in energy between staggered and eclipsed conformations is due to closed-shell repulsion.[12] It therefore appears that alteration in closed-shell repulsions by electronegative 7-substituents could indeed play an important role in determining the facility of *endo* attack in norbornenyl systems.

This argument also explains why only the rate of *exo-anti* attack is sensitive to the 7-substituents. Both *exo-anti* and *endo-anti* attacks of electrophiles are decelerated by an electron-withdrawing substituent because of the lowering of π-HOMO energy. However, the *endo* attack is compensated by reduced closed-shell repulsive interaction. In the same manner, both the *exo-anti* and *endo-anti* attacks are accelerated by an electron-donating substituents because donors [redacted] density at C-6, and facilitates bridging between C_6 and C_2 and increases the rate of solvolysis. Counteracting this in the *endo* epimer, **3**, is the increase in repulsion between C_6 and the leaving tosylate anion, an effect which is absent for the *exo* epimer. Consequently the *endo* isomer, **1**, will display a lower sensitivity towards the nature of R than the *exo* epimer, **4**.[13] Electrostatic effects may also play a role, since C_7 becomes partially positively charged with the attachment of an electron-withdrawing substituent.[14]

We attribute the slight lowering of activation energies of *endo-syn* attack with respect to *endo-anti* attack by 7-alkoxy substituents to through-space effects. These substituents have oxygen lone-pairs situated such that they are in the proximity of the *syn* π-orbitals. Electrophilic attack on the opposite (*endo-syn*) side of the double bond is facilitated. This through-space effect has been proposed for rigid systems by others,[15] and has been postulated recently to account for the stereochemistry of hydroboration[16] and oxymercuration[17] of acyclic chiral homoallylic ethers. This effect is larger for **HCCP** cycloadditions than it is for mesitonitrile oxide and dichlorocarbene cycloadditions,[18-19] and is consistent with larger charge-transfer in the transition state for the hexachlorocyclopentadiene reactions.

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References and Notes

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