Thus a nonlinear AD diagram and a linear ADQ2 (absorption difference quotient of second order) diagram indicate two independent reactions ($s = 2$). Nonlinear ADQ2 diagrams indicate higher order reactions ($s > 2$).[35]

The Case s > 2. Higher order diagrams have been developed[36] and interpreted in an analogous manner. They demand very high precision in measurement. If rate constants are very different from the others, lower order diagrams may be linear in restricted regions of the diagram.

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(35) In some very special cases, e.g., if a linear ADQ2 plot happens to be parallel to an axis or goes through the origin, $s = 2$ and $s = 3$ cannot be discriminated by ADQ2 diagrams.

(36) Blume, R. Ph.D. Thesis, Tübingen, 1975.

(37) In cooperation with H. Mauser, Frauenstrasse, 7410 Reutlingen, West Germany.

Theoretical Studies of Nucleophilic Additions of Organocopper Reagents to Acrolein. Rationalization of the Differences in Regioselectivity in the Reactions of Methylcopper and Methyllithium

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Received August 16, 1988

Abstract: Ab initio molecular orbital studies of the addition of methyllithium and methylcopper to acrolein have been performed. Transition states for addition to the carbonyl group (which gives the alcohol as the final product), to the carbon–carbon double bond, and across the π system (both of which lead to formation of the saturated ketone) have been located. Calculations at the HF/3-21G (with full geometry optimization), HF/6-31G*, and MP2/6-31G* levels indicate that reaction of methyllithium with the carbonyl group is preferred to conjugate addition to the double bond, in agreement with experimental data. In the computations of all species containing copper, an effective core potential was used in place of the inner-shell electrons, while the valence (3d, 4s, and 4p) orbitals were represented by basis sets of single- and double-ζ quality. Calculations at the HF/3-21G-ECP(SZ) and -ECP(DZ) levels were performed with full geometry optimization, and single-point energy calculations were carried out at the HF/6-31G*-ECP(DZ) and, in selected cases, MP2/6-31G*-ECP(DZ) and MP4/6-31G*-ECP(DZ) levels. All calculations indicate that 1,4-addition across the π system via a six-membered transition state is greatly favored over 1,2-addition. 1,4-Addition via a four-membered transition state is calculated to be slightly disfavored with respect to 1,2-addition to the carbonyl group. Possible reasons for the observed preference for 1,4-addition in solution are discussed.

The use of transition metal organometallic compounds in organic synthesis is a topic of established importance.[1] Among the several classes of systems which have found extensive application in the field, organocopper reagents deserve particular recognition. Ever since the early work by Kharasch and Tawney,[2] who pioneered the use of cuprous salts as catalysts in Grignard reactions, the number and scope of reagents containing copper has increased considerably.[3] The two most frequently used are the dialkylcuprates (generally with lithium as the counterion) and the alkylcopper–Lewis acid complexes. The latter species have been found to add regioselectivity (and often with high stereoselectivity) to the C=C bond of enones and enoates,[4] and to react with allylic substrates in S_N2' fashion almost exclusively.[5] The most common Lewis acids are boron trifluoride and aluminum trichloride, but several others have been employed effectively.[4] The precise mechanism of action is not known with certainty; however, Ganem has shown that the nucleophile and the Lewis acid act independently in the reaction of $LiCH_3$–BF_3 with oxiranes and oxetanes.[6] Here, the oxygen atom coordinates a molecule of boron trifluoride while the anionic methyl carbon attacks the C–O bond. This type of mechanism is likely to be valid whenever the electrophilic substrate contains strongly coordinating oxygen atoms.[4,7,8] Stereochemical studies of the addition of $MeCu\cdot AlCl_3$ to β'-cyclopropyl-α,β-enones show that the reaction mechanism does not involve electron transfer,[9] which has been postulated for the conjugate addition of lithium dialkylcuprates.[10]

This propensity for conjugate (1,4-) addition to α,β-unsaturated ketones (and esters) stands in sharp contrast to the preference

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(1) *Transition Metal Organometallics in Organic Synthesis*; Alper, H., Ed.; Academic Press: New York, 1976; Vol. 1.

(2) Kharasch, M. S.; Tawney, P. O. *J. Am. Chem. Soc.* **1941**, *63*, 2308.

(3) Posner, G. H. *An Introduction to Synthesis Using Organocopper Reagents*; Wiley: New York, 1980. Collman, J. P.; Hegedus, L. S.; Norton, J. R.; Finke, R. G. *Principles and Applications of Organotransition Metal Chemistry*; University Science Books: Mill Valley, CA, 1987; Chapter 14.

(4) Yamamoto, Y. *Angew. Chem., Intl. Ed. Engl.* **1986**, *25*, 947.

(5) Goering, H. L.; Seitz, E. P., Jr.; Tseng, C. C. *J. Org. Chem.* **1981**, *46*, 5304. Goering, H. L.; Kantner, S. S.; Tseng, C. C. *J. Org. Chem.* **1983**, *48*, 715.

(6) Eis, M. J.; Wrobel, J. E.; Ganem, B. *J. Am. Chem. Soc.* **1984**, *106*, 3693.

(7) This seems true even for substrates other than α,β-unsaturated carbonyl compounds. Thus, acetals react with alkylcopper–Lewis acid reagents to give ethers: Ghribi, A.; Alexakis, A.; Normant, J. F. *Tetrahedron Lett.* **1984**, *25*, 3075.

(8) In contrast, Maruyama and Yamamoto have suggested that the reaction of $RCu\cdot BF_3$ with allylic halides involves the preliminary formation of an ate complex, $Cu^+BF_3(Me)^-$: Maruyama, K.; Yamamoto, Y. *J. Am. Chem. Soc.* **1977**, *99*, 8068.

(9) Ibuka, T.; Tabushi, E. *J. Chem. Soc., Chem. Commun.* **1982**, 703. Ibuka, T.; Tabushi, E.; Yasuda, M. *Chem. Pharm. Bull.* **1983**, *31*, 128.

(10) House, H. O. *Acc. Chem. Res.* **1976**, *9*, 59. House, H. O.; Chu, C-Y. *J. Org. Chem.* **1976**, *41*, 3083. Yamamoto, Y.; Shinji, N.; Ibuka, T. *J. Am. Chem. Soc.* **1988**, *110*, 617. Evidence *against* this type of mechanism has been found by Bertz and Cook: Bertz, S. H.; Dabbagh, G.; Cook, J. M.; Honkan, V. *J. Org. Chem.* **1984**, *49*, 1739; and by Jullien: Frejaville, C.; Jullien, R.; Stahl-Lariviere, H.; Wanat, M.; Zann, D. *Tetrahedron* **1982**, *38*, 2671.

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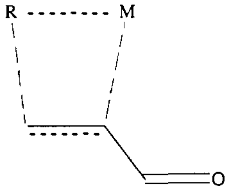
exhibited by alkyllithium reagents for addition to the carbonyl group of enones (1,2-addition). For sulfur-stabilized organolithium reagents, the regioselectivity is influenced by the extent to which ion pairs are present in solution[11] Nonetheless, it is only under conditions of low temperture and in the presence of solvents such as hexamethylphosphoramide (which favors solvent-separated ion pairs) that 1,4-addition starts to predominate. The difference in behavior between alkyllithium and organocopper reagents is very useful in organic synthesis; however, the reasons for the opposite regioselectivities are not fully understood, although an interpretation based on the relative "softness" of the nucleophiles has been offered.[12] Another mechanistic issue of interest concerns the mode of 1,4-addition, which produces a saturated carbonyl compound. This reaction may proceed either via addition across the C=C bond (**1**) or through a six-membered transition state (**2**) in which both ends of the conjugated system interact with the nucleophilic reagent. Obviously, a cyclic structure such as **2** may be involved only if an s-syn conformation of the enone or enoate is attainable. While this is impossible in small-membered cyclic ketones or in lactones, **2** is a viable alternative to **1** in acyclic molecules. When the cation is Cu^+, the reaction intermediates arising from **1** and **2** are respectively an α-cuprio ketone (or ester) and a copper enolate. Using a stereochemical probe, Yamamoto has recently demonstrated that the reaction of $BuCu{\cdot}BF_3$ with acyclic esters does indeed yield the copper enolate.[13] As the authors themselves point out, however, this does not prove that the reaction proceeds through transition state **2**. The α-cuprio ester (obtained via **1**) could conceivably be a short-lived reaction intermediate, which could then rapidly rearrange to the enolate.[14,15] Moreover, the issue of the mechanism of conjugate addition to other systems, notably enones, remains unresolved.



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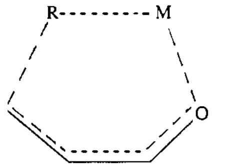

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These and other intriguing aspects of organocopper chemistry are worthy of closer theoretical scrutiny. In this first report, we shall describe theoretical studies which address the issue of the regioselectivity of nucleophilic additions to conjugated systems. We have pursued an ab initio molecular orbital investigation of the 1,4- and 1,2-additions of methylcopper and methylcopper–borane to acrolein, which serves as a simple model for α,β-unsaturated carbonyl compounds. We have likewise carried out an analysis of the analogous addition reactions of methyllithium. The latter calculations serve for comparison purposes, but at the same time they are of considerable interest in themselves. In fact, while the closely related nucleophilic additions to carbonyl compounds have been extensively studied,[16-18] no detailed analysis has been performed of the addition of nucleophiles to the C=C bond of conjugated systems.[19,20] Although alkyllithium reagents do not give conjugate addition reactions, other nucleophilic reagents of widespread use, notably Grignard reagents, do so; methyllithium serves as a computationally inexpensive model for such systems. The calculations described in this paper are aimed at rationalizing the observed differences in the mode of addition of organolithium and -copper species. We have also addressed the question of the mechanism of conjugate addition of alkylcopper–Lewis acid complexes.[4]

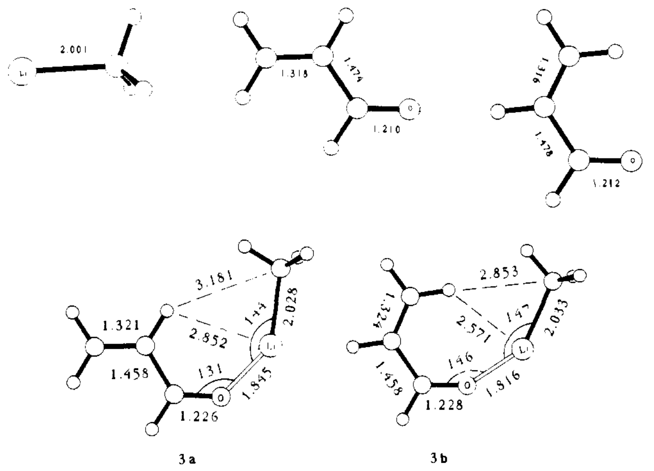

Figure 1. HF/3-21G optimized structures (in ångstroms and degrees) of methyllithium, *s-trans-* and *s-cis*-acrolein, and the σ complexes of methyllithium with acrolein (**3a** and **3b**). C_s symmetry is assumed in the latter.

Computational Methods

The restricted Hartree–Fock method was used throughout for geometry optimization of reactants, complexes, and transition structures.[21] The 3-21G[22] basis set was used for geometry optimizations for all atoms except copper. For the latter, the inner-shell (from 1st to 3p) electrons were replaced by an effective core potential (ECP). The potential parameters employed in our calculations are those given by Hay and Wadt.[23,24] The remaining electrons were described by basis sets of

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[11] Cohen, T.; Abraham, W. D.; Meyers, M. *J. Am. Chem. Soc.* **1987**, *109*, 7923.

[12] Deschamps, B.; Anh, N. T.; Seyden-Penne, J. *Tetrahedron Lett.* **1973**, 527. For a general discussion on the subject of "hard" and "soft" nucleophiles, see: Fleming, I. *Frontier Orbitals and Organic Chemical Reactions*; Wiley: London, 1976; pp 34–66.

[13] Yamamoto, Y.; Yamada, J.-I.; Uyehara, T. *J. Am. Chem. Soc.* **1987**, *109*, 5820.

[14] Several authors have suggested the intermediacy of α-cupriocarbonyl intermediates in addition reaction to conjugated systems. Some examples: (a) Amos, R. A.; Katzenellenbogen, J. A. *J. Org. Chem.* **1978**, *43*, 555. (b) Four, P.; Riviere, H.; Tang, P. W. *Tetrahedron Lett.* **1977**, 3879. (c) Berlan, J.; Battioni, J.-P.; Koosha, K. *J. Organomet. Chem.* **1978**, *152*, 359. Posner and Lentz have noted the effect of even a small concentration of cuprous ions on the stereoselectivity of alkylation of lithium enolates: Posner, G. H.; Lentz, *J. Am. Chem. Soc.* **1979**, *101*, 934. The authors suggest that copper enolates may be involved, probably very dissimilar in structure from the lithium enolates.

[15] A vinylcopper species is believed to be the intermediate in the additions to ynones and ynoates: Yamamoto, Y.; Yatagai, H.; Maruyama, K. *J. Org. Chem.* **1979**, *44*, 1744, and references therein.

[16] Most theoretical models seem to support the conclusions of Felkin and Anh that attack occurs anti to a vicinal bond, in order to minimize torsional strain in the transition state: (a) Cherest, M.; Felkin, H. *Tetrahedron Lett.* **1968**, 2205. (b) Anh, T.; Eisenstein, O. *Nouv. J. Chim.* **1977**, *1*, 61. (c) Wipke, W. T.; Gund, P. *J. Am. Chem. Soc.* **1976**, *98*, 8107. (d) Wu, Y.-D.; Houk, K. N. *J. Am. Chem. Soc.* **1987**, *109*, 908.

[17] Cieplak has suggested that nucleophilic attack should occur *anti* to the best electron-donating group: Cieplak, A. S. *J. Am. Chem. Soc.* **1981**, *103*, 4540. See also: Srivastava, S.; LeNoble, W. J. *J. Am. Chem. Soc.* **1987**, *109*, 5874. However, experimental evidence against Cieplak's interpretation has been recently provided by Houk: Mukherjee, D.; Wu, Y.-D.; Fronczek, F. R.; Houk, K. N. *J. Am. Chem. Soc.* **1988**, *110*, 3328.

[18] The effect of solvent (water) molecules on the nucleophilic attack of the hydroxide anion on formaldehyde has also been modeled by ab initio calculations and Monte Carlo simulations: Madura, J. D.; Jorgensen, W. L. *J. Am. Chem. Soc.* **1986**, *108*, 2517. An ab initio MO study of the effect of water molecules on the hydration of formaldehyde has been performed by Maggiora, Schowen, and co-workers: Williams, I. H.; Spangler, D.; Femec, D. A.; Maggiora, G. M.; Schowen, R. L. *J. Am. Chem. Soc.* **1983**, *105*, 31.

[19] An ab initio SCF–MO study of the nucleophilic attack of an enamine on acrolein has been performed: Sevin, A.; Tortajada, J.; Pfau, M. *J. Org. Chem.* **1986**, *51*, 2671.

[20] Theoretical studies of nucleophilic additions to isolated carbon–carbon double and triple bonds have been reported by Houk, Schleyer, and co-workers: Houk, K. N.; Rondan, N. G.; Schleyer, P. v. R.; Kaufmann, E.; Clark, T. *J. Am. Chem. Soc.* **1985**, *107*, 2821. See also: Schleyer, P. v. R.; Kos, A. J.; Kaufmann, E. *J. Am. Chem. Soc.* **1983**, *105*, 7617. See also: Nagase, S.; Houk, K. N. *Tetrahedron Lett.* **1982**, *23*, 19.

[21] The GAUSSIAN 82 program was used throughout: Binkley, J. S.; Frisch, M. J.; DeFrees, D. J.; Raghavachari, K.; Whiteside, R. A.; Schlegel, H. B.; Pople, J. A. GAUSSIAN 82, Department of Chemistry, Carnegie-Mellon University, Pittsburgh, PA

[22] (a) 3-21G basis set: Binkley, J. S.; Pople, J. A.; Hehre, W. J. *J. Am. Chem. Soc.* **1980**, *102*, 939. (b) 6-31G* basis set: Hariharan, P. C.; Pople, J. A. *Theor. Chim. Acta* **1973**, *28*, 213.

[23] Hay, P. J.; Wadt, W. R. *J. Chem. Phys.* **1985**, *82*, 270, 284. For a description of the general procedure for the derivation of ECP parameters, see: Goddard, W. A., III; Kahn, L. R. *J. Chem. Phys.* **1972**, *56*, 2685. Melius, C. F.; Goddard, W. A., III *Phys. Rev. A* **1974**, *10*, 1528.

Table I. HF/3-21G, HF/6-31G*, and MP2/6-31G* Energies of Complexation ($E_{\sigma\text{-}r}$) of Acrolein with Methyllithium and Methylcopper at the HF/3-21G Optimized Geometries

	$E_{\sigma\text{-}r}$		
σ complex	HF/3-21G[a]	HF/6-31G*[b]	MP2/6-31G*[b]
3a	−31.66	−21.62	−21.63
3b	−32.37	−20.05	−20.01
4a	−24.95 [−21.55][c]	−22.04	−17.66
4b	−24.69 [−21.27][c]	−21.78	
4c	−24.39 [−20.80][c]		
4d	−24.68 [−21.12][c]		

[a] 3-21G-ECP(DZ) for **4a–d**. [b] 6-31G*-ECP(DZ) for **4a–d**. [c] 3-21G-ECP(SZ).

single- and double-ζ quality[23] in two separate sets of calculations. We shall denote these computational procedures with the terms RHF/ECP-(SZ) and RHF/ECP(DZ), respectively. Further energy calculations on the optimized geometries were performed at the Hartree-Fock level of theory with the 6-31G* basis set.[22] For a limited number of structures (vide infra), MP2[25]/6-31G* energy calculations were also carried out to test the effect of correlation energy on the relative energies of the species involved.

Certain assumptions were necessary because of the very large size of the calculations involved. Thus, all calculations deal with monomeric methyllithium and methylcopper, even though both species exist as aggregates.[26] Methylcopper itself is a yellow polymeric solid, insoluble in common organic solvents such as ether; it is therefore usually used in soluble form as a complex with ligands (typically trialkylphosphines[27]) or Lewis acids.[13] Schleyer, Houk, and co-workers have shown that the main features of the reactant complex and of the transition state are similar for the addition to formaldehyde of methyllithium and of its dimer,[28] which justifies the assumption in the present work. Another assumption was made in the calculations modeling the reactions of organocopper–Lewis acid systems. The Lewis acid used in these calculations is a borane molecule, whereas typical reagents employed experimentally are boron trifluoride and aluminum trichloride.[4] However, theoretical studies of the complexes of ammonia with borane and boron trifluoride suggest that the energies of complexation are rather similar.[29] Similarly, acrolein is used as a model for the reaction of α,β-unsaturated carbonyl compounds. While it is true that enals are more reactive than enones at the carbonyl group,[30] our choice is adequate for the purpose of comparing methylcopper and methyllithium.

Results and Discussion

Reactants and Complexes. HF/3-21G geometry optimizations of methyllithium[28] and acrolein[31] have been previously reported in the literature. The optimization of methylcopper with the HF/3-21G-ECP(SZ) procedure gave a structure having a rather long Cu- -C bond of 2.161 Å. The HF/3-21G-ECP(DZ) optimization resulted in a shorter bond length of 2.040 Å. This value is in agreement with the measured Cu–C bond length of 2.04 Å (±0.05 Å) in the crystal structure of an alkylcopper tetramer.[32] As expected, the copper–carbon bond is less strongly polarized than the lithium–carbon bond; the calculated total charge on the transition metal is about +0.3 e (regardless of the method of calculation), while the charge on lithium is +0.5 e.

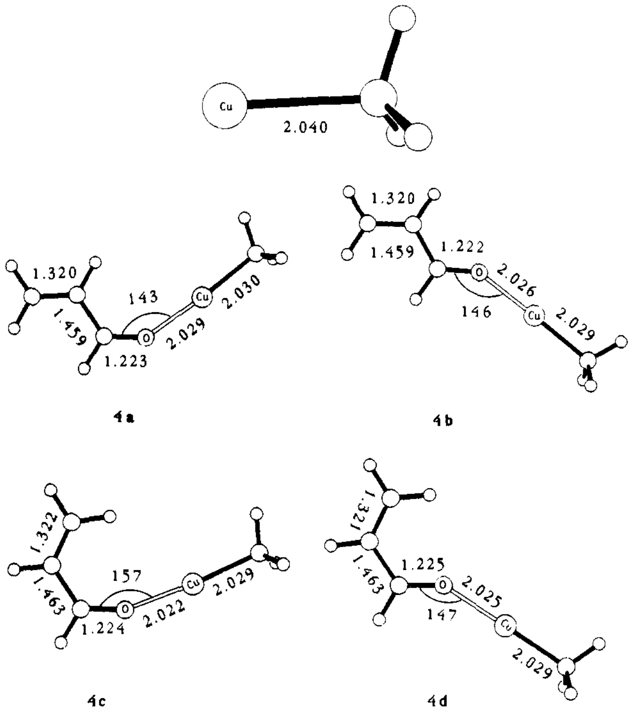

Figure 2. HF/3-21G-ECP(DZ) optimized structures (in ångstroms and degrees) of methylcopper and of the σ complexes of methylcopper with acrolein (**4a** and **4b**). C_s symmetry is assumed in the latter.

We next calculated the geometries and energies of complexation of acrolein with methyllithium and methylcopper. Figure 1 shows some essential geometric parameters of the HF/3-21G optimized structures of the σ complexes[33] of methyllithium with acrolein (**3a**,**3b**). The structures of the isolated reactants are also shown for comparison. The analogous σ complexes for methylcopper (**4a–d**), optimized at the HF/3-21G-ECP(DZ) level, are shown in Figure 2, together with the structure of the methylcopper molecule. In Table I we give the values of the complexation energy $E_{\sigma\text{-}r}$, which we define as the difference between the energy of the σ complex and the sum of the energies of the isolated reactants. Four distinct complexes were located in the case of methylcopper. **4a** and **4c** correspond to the methyllithium complexes **3a** and **3b**, respectively, while **4b** and **4d** have no counterparts. Any attempt to optimize methyllithium complexes having structures similar to **4b** and **4d** gave **3a** and **3b**. We attribute this result to a combination of two effects, both originating from the highly polar nature of the Li–C bond. The first is the tendency for this bond to align itself with the strongly polarized C=O bond, which would give a linear C=O- -Li arrangement. The second is the attractive electrostatic interaction between the partially positively charged hydrogen atoms of the vinyl group and the electrons of the lithium–carbon. Evidence for interaction comes from the fact that the O–Li–C angle deviates appreciably from linearity, bringing the methyllithium molecule and the relevant olefinic hydrogen closer together; in contrast, the O- -Cu—C angle in **4a–d** is essentially equal to 180° in all cases. In Figure 1, dashed lines are

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(24) The procedure on which the code was based is described in: Davidson, E. R.; McMurchie, L. E. *J. Comp. Phys.* **1981**, *44*, 289. The computational implementation is due to: Martin, L. R., unpublished.

(25) Binkley, J. S.; Pople, J. A. *Int. J. Quantum Chem.* **1975**, *9*, 229. Pople, J. A.; Binkley, J. S.; Krishnan, R. *Int. J. Quantum Chem. Symp.* **1976**, *10*, 1.

(26) Butyllithium exists mainly as the tetramer in tetrahydrofuran, with the dimer being present in minor quantities: (a) McGarrity, J. F.; Ogle, C. A. *J. Am. Chem. Soc.* **1985**, *107*, 1805. Methylcopper: Pearson, R. G.; Gregory, C. D. *J. Am. Chem. Soc.* **1976**, *98*, 4098.

(27) Suzuki, M.; Suzuki, T.; Kawagishi, T.; Noyori, R. *Tetrahedron Lett.* **1980**, *21*, 1247.

(28) Kaufmann, E.; Schleyer, P. v. R.; Wu, Y.-D.; Houk, K. N. *J. Am. Chem. Soc.* **1985**, *107*, 5560. See also: Bachrach, S. M.; Streitweiser, A., Jr. *J. Am. Chem. Soc.* **1986**, *108*, 3946. It must be noted that although butyllithium is a tetramer in THF,[26] it reacts more readily as the dimer: McGarrity, J. F.; Ogle, C. A.; Brich, Z.; Loosli, H.-R. *J. Am. Chem. Soc.* **1985**, *107*, 1810.

(29) Umeyama, H.; Morokuma, K. *J. Am. Chem. Soc.* **1976**, *98*, 7208.

(30) March, J. *Advanced Organic Chemistry*, 3rd ed.; Wiley: New York, 1985; pp 711–719.

(31) Loncharich, R. J.; Schwartz, T. R.; Houk, K. N. *J. Am. Chem. Soc.* **1987**, *109*, 14.

(32) Jarvis, J. A. J.; Kilbourn, B. T.; Pearce, R.; Lappert, M. F. *J. Chem. Soc., Chem. Commun.* **1973**, 475.

(33) We also attempted to locate a π complex of acrolein and methyllithium, having the lithium atom lying over the double bond (cf. ref 20); however, regardless of the starting geometry, the lithium atom tends to move toward the carbonyl oxygen at the same time as it approaches the molecular plane of acrolein. In solution, a π complex is a distinct intermediate in the reaction of lithium dimethylcuprate with cinnamate esters: (a) Hallnemo, G.; Olsson, T.; Ullenius, C. *J. Organomet. Chem.* **1985**, *282*, 133. The same authors suggest that another intermediate, probably a σ complex, is also present at lower temperatures. A similar structure has been postulated by Krauss and Smith: (b) Krauss, S. R.; Smith, S. G. *J. Am. Chem. Soc.* **1981**, *103*, 141.

drawn from the lithium and carbon atoms to the relevant hydrogen atoms, to indicate the presence of weak interactions. Small, positive (ca. +0.01) electronic populations are calculated for the Li- -H and C- -H "bonds" in **3a** and **3b**. This type of attraction does not seem to stem from basis set incompleteness; in fact, HF/3-21G and HF/6-31G*//HF-21G calculations both favor **3a** (by 0.57 and 0.83 kcal/mol, respectively) over the corresponding structure optimized with the constraint of a linear O- -Li—C angle.

The structure of each fragment in complexes **3a**,**b** and **4a**–**d** differs little from that of the isolated reactant. In all cases, the C=O bond is slightly longer than in acrolein, particularly for the methyllithium complexes. Complexation to the metal center enhances the polarization and, therefore, the single-bond character of the C=O bond. An analogous, stronger effect has also been observed in the calculation of the acrolein–lithium cation complex.[31] The Li–C bond length of methyllithium is also slightly lengthened (from about 2.00 Å to about 2.03 Å), while the Cu–C bond length decreases by 0.01 Å in the complexes.

At the HF/3-21G level, the two methyllithium species are close in energy, as are all methylcopper species (with the exception of the sterically encumbered **4c**). On the other hand, HF/6-31G* single-point energy calculations gave an appreciable preference for the complexes of the s-trans conformer of acrolein **3a** with respect to the s-syn conformer complex. As shown by Houk and co-workers, the two acrolein conformers have the same energy at the HF/3-21G level, but both HF-6-31G* geometry optimization and HF/6-31G*//HF/3-21G calculations favor the s-trans conformer by about 1.7 kcal/mol.[31] Thus, complexation to the metal simply strengthens the conformational preference exhibited by the starting material. The same authors have observed an analogous effect for the complexation of acrylic acid and methyl acrylate with a molecule of borane.

In complexes **3a**,**b**, the calculated complexation energies decrease from the HF-3-21G to the HF/6-31G* level. For example, **3a** is 31.66 kcal/mol more stable than the individual reactants according to the HF/3-21-G calculation, but only 21.62 kcal/mol more stable at the HF/6-31G* level. MP2/6-31G*//HF/3-21G calculations were also carried out on acrolein, methyllithium, and complexes **3a** and **3b**. The effect of electron correlation was found to be very modest: both the energy difference between **3a** and **3b** and the stabilization with respect to the isolated reactants were virtually unchanged from the HF/6-31G* value. In the case of the methylcopper complexes, HF/6-31G*-ECP(DZ) calculations were performed on the HF/3-21G-ECP(DZ) optimized geometries. These calculations confirm a slight preference for **4a** over **4b** (0.26 kcal/mol with the larger basis set) and yield a value of 22.04 kcal/mol for the complexation energy in **4a**, slightly lower than the 24.95 kcal/mol calculated with the 3-21G-ECP(DZ) basis set. We also probed the effect of electron correlation on the complexation energy by performing an MP2/6-31G*-ECP(DZ) energy calculation on **4a**; the complexation energy was found to decrease to 17.66 kcal/mol.

For comparison purposes, geometry optimizations of **4a**,**b** were also carried out at the HF/3-21G-ECP(SZ) level. The results obtained in this manner are similar to those derived from the HF/3-21G-ECP(DZ) calculations (see Table I). The relative energies of **4a**,**b** are very similar, and the complexation energies are only slightly smaller with the smaller basis set. The geometries are essentially the same, except for a longer Cu–C bond when the SZ basis set is used.

Transition States for the Nucleophilic Addition of Methyllithium. The transition structures for the addition of methyllithium to acrolein are shown in Figure 3. Three modes of addition were considered: (a) addition to the C=C bond via a four-membered cyclic transition state (**5a**), (b) addition to both ends of the conjugated system via a six-membered structure (**5b**), and (c) addition to the C=O bond of *s-trans*-acrolein (**5c**) and *s-cis*-acrolein (**5d**). In Table II we report the activation energies of the three transition structures relative to σ-complex **3a** ($E_{ts-\sigma}$) calculated at the HF/3-21G, HF/6-31G*//HF/3-21G, and MP2/6-31G*//HF/3-21G levels. One more transition structure is conceivable. This would correspond to **5a**, but with an s-cis conformation for the acrolein moiety. Our attempts to locate such a transition state failed, however, as the lithium atom shifted from its starting position (over the C=C bond) toward the oxygen atom. Optimization was not completed, but it is likely that structure **5b** would have been reobtained from this procedure. The energy was found to decrease at each successive point in the optimization, but it remained higher than that of **5b**.

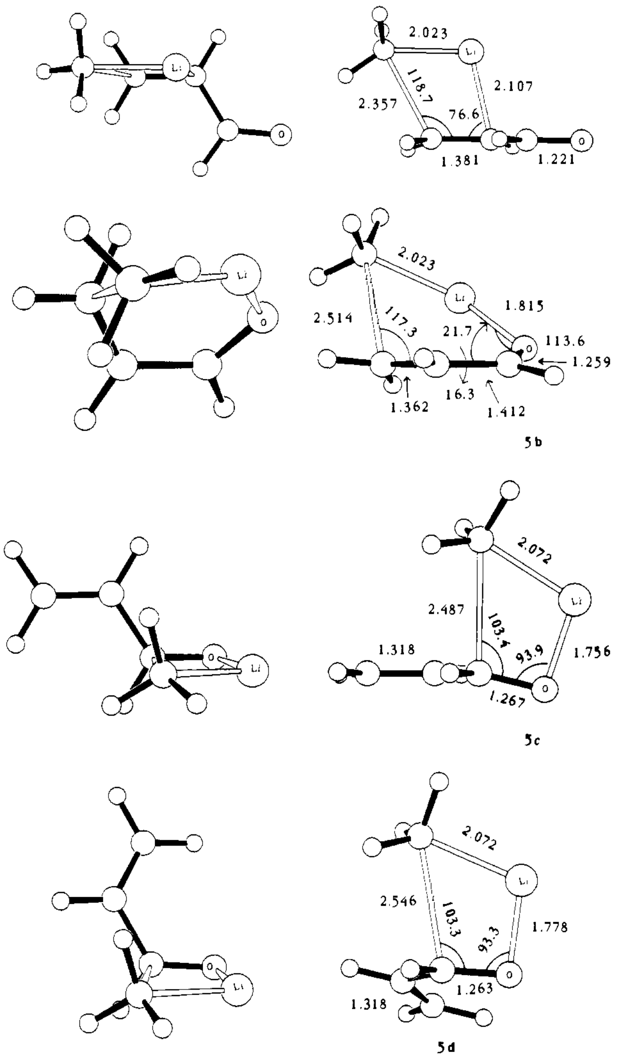

Figure 3. Transition structures (in ångstroms and degrees) for the addition of methyllithium to acrolein: (a) 1,4-addition via a four-membered transition structure; (b) 1,4-addition via a six-membered transition structure; (c and d) 1,2-addition to *s-trans-* and *s-cis*-acrolein, respectively.

Table II. Activation Energies (in kcal/mol) of Transition Structures **5a**–**d** Calculated with Reference to σ-Complex **3a**[a]

	$E_{ts-\sigma}$		
transition structure	HF/3-21G	HF/6-31G*	MP2/6-31G*
5a	32.73	27.90	16.31
5b	13.45	15.83	5.86
5c	12.19	11.55	4.34
5d	11.70	11.54	5.17

[a] All energies are calculated at the HF/3-21G optimized geometries.

We note from the table that **5c** and **5d** are similar in energy at all levels of calculation. This is noteworthy, in light of the preference for the s-trans conformation in the reactant acrolein molecule. We shall further elaborate on this point later in the paper; first, however, we wish to compare these transition structures to **5a** and **5b**. In our subsequent discussion, we shall refer to **5c** alone as representative of the two transition states for 1,2-addition. Our choice is prompted by the fact that **5c** has the lower energy at the highest level of calculation performed; however,

Table III. Total Interaction Energy (INT) and Individual Energy Components of INT in **5a–c** and **5a′** (in kcal/mol)[a]

transition structure	DEF_A	DEF_B	INT	ES	EX	CTPLX (A→B)	CTPLX (B→A)	R
				HF/3-21G				
5a	7.4	6.0	−12.9	−53.8	95.3	−17.7	−41.3	4.6
5b	10.3	4.4	−33.6	−49.5	58.5	−13.1	−25.4	−4.1
5c	5.3	3.8	−29.3	−55.1	71.6	−15.8	−25.7	−4.3
5a′[b]	7.4	6.5	−12.8	−41.2	71.6	−14.4	−31.6	2.7
				HF/6-31G*				
5a	7.2	5.9	−6.8	−55.9	100.3	−11.2	−41.3	1.3

[a] Here A is the acrolein moiety, B methyllithium. [b] See text.

similar arguments can be assumed to hold even for **5d**, given the similarity in geometry (Figure 3) as well as in energy of the two structures.

At the HF/3-21G level, transition state **5c** is favored over **5b** by 1.3 kcal/mol, and over **5a** by 20.6 kcal/mol. The large preference for both **5b** and **5c** over **5a** is understandable, in view of the incipient formation of an O-enolate in the first two cases and of a C-enolate in the third. What is more remarkable is the preference for **5c** over **5b**, even though the former is a four-centered cyclic transition structure, formally forbidden by symmetry, while the latter is a symmetry-allowed, six-electron cyclic array. Evidently, orbital symmetry considerations are relatively unimportant, as has also been suggested for the addition of methyllithium to formaldehyde.[28] Both transition states (as well as **5a**) are asynchronous, with a rather short lithium–oxygen bond; however, **5c** is favored because of the strong interaction between the nucleophilic methyl group and the highly positively charged carbonyl carbon. The analogous methyl–olefinic carbon interaction in **5b** is considerably weaker. The difference in the calculated bond orders is indicative: the values for the forming C- -C bonds in **5b** and **5c** are 0.026 and 0.067, respectively.

HF/6-31G* and MP2/6-31G* calculations yield a slightly different but qualitatively unchanged picture (Table II). At the Hartree-Fock level, the difference in stability between **5c** and **5b** increases to 4.3 kcal/mol. This reflects once again the stabilizing effect of the larger basis set on the s-trans conformation of the C=C—C=O group (present in **5c**). Inclusion of correlation energy, however, has a roughly equal and opposite effect; the calculated preference for **5c** at the MP2/6-31G* level is thus 1.5 kcal/mol, which is similar to the HF/3-21G value. Transition structure **5a** is the least stable of the three at all levels of computation, but the energy gap between this structure and the other two decreases substantially when the 6-31G* basis set is used. Thus, **5a** is found to be only 16.4 kcal/mol less stable than **5c**. Most likely, the results obtained with the smaller basis set are affected by basis set superposition error (BSSE).[34] This effect is expected to be especially important for the oxygen–lithium interaction in **5b** and **5c**.[35] This error is much smaller with the extended 6-31G* basis set, so that the spurious stabilization of these two structures disappears. In this respect, these results parallel the ones obtained for the energy of complexation of methyllithium with acrolein in σ complexes **3a** and **3b**. The inclusion of correlation energy further decreases the **5a**–**5c** gap to 12.0 kcal/mol.

The geometry of each structure deserves further comment. **5c** and its counterpart **5d** are both quite similar to the transition state for attack of methyllithium on formaldehyde,[28] with a vinyl group replacing a hydrogen atom. Formation of both bonds takes place roughly at right angles to the plane of acrolein. In contrast, the C—C=O- -Li torsional angle in **5b** is only 21.7°, whereas the C—C=C—C angle (−73.9°) is again close to −90°. The lithium atom prefers to lie as close to the molecular plane as possible, since the in-plane oxygen lone pair coordinates it more strongly than the π system. On the other hand, nucleophilic attack of the methyl group is favored to take place at right angles to the π system, so as to maximize the overlap between the filled orbital on carbon and the low-lying vacant orbitals of the acrolein molecule. In order for both interactions to be satisfied, a 16.3° rotation about the central bond is necessary. This transition structure is therefore characterized by a marked asymmetry, both in the timing of bond formation and in the trajectory of attack to the two ends of the conjugated system.

In both **5b** and **5c** (or **5d**) the angle of attack of the methyl group is close to the Burgi–Dunitz angle.[36] The Li- -O=C bond angle is also larger than 90°; however, the analogous Li- -C=C angle in **5a** is only 76.6°, and the C- -C=C angle is consequently rather large, 118.7°. In essence, the methyllithium moiety is "shifted" with respect to the C=C bond, so that the lithium atom lies almost directly above the center of the bond. The two atom–atom populations are, in fact, comparable (0.065 for the Li- -Cα bond and 0.114 for the Li- -Cβ bond). Indeed, the Li- -Cβ bond (2.235 Å) is not much longer than the Li- -Cα bond (2.107 Å), and it is actually shorter than the forming C- -Cβ bond (2.357 Å; the bond population here is 0.064). This geometry resembles one for *electrophilic* addition to a double bond, rather than nucleophilic addition; indeed, this structure is reminiscent of the transition structures for addition of methyllithium to ethylene and to acetylene.[20] The interaction between the partially charged lithium and the double bond is dominant, while carbon–carbon bond formation is still at an early stage. In this respect, this structure is similar to **5c**.

While the qualitative arguments given above are justifiable, even in the light of previous theoretical studies of nucleophilic additions of methyllithium,[28] it was desirable to assess quantitatively the relative importance of electrostatic interactions and other effects, such as charge transfer (including HOMO–LUMO interactions). We therefore carried out an energy decomposition analysis of the interaction between the transition-state fragments (methyllithium and acrolein) in **5a–c**, using the Kitaura–Morokuma scheme. The theory has been given elsewhere;[37] here we summarize the relevant points. Using this procedure, the total interaction energy (in this case, the difference between the transition state energy and the sum of the energies of the fragments) is expressed as a sum of electrostatic (ES), charge-transfer (CT), exchange (EX), and polarization (PL) terms. Thus we can write

$$\mathrm{INT} = \mathrm{ES} + \mathrm{EX} + \mathrm{CT} + \mathrm{PL} + \mathrm{MIX}$$

The last term of the equation, MIX, originates from the coupling of other terms (e.q., charge transfer and polarization), and it is not calculated explicitly, but simply as the difference between INT and the sum of the other terms. In practice, MIX is rather large when the interaction between fragments is strong; it is therefore desirable to adopt an alternative scheme that explicitly takes strong coupling into account. In this scheme INT is expressed as[38]

$$\mathrm{INT} = \mathrm{ES} + \mathrm{EX} + \mathrm{CTPLX(A{\rightarrow}B)} + \mathrm{CTPLX(B{\rightarrow}A)} + \mathrm{R}$$

The first of the two new terms (CTPLX(A→B)) is obtained by subtracting ES and EX from the energy in which the interactions between filled A orbitals and vacant B orbitals, filled

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(34) Boys, S. F.; Bernardi, F. *Mol. Phys.* **1970**, *19*, 553.

(35) BSSE is very significant in hydrogen-bonded systems. For leading references and an improved method for counterpoise corrections, see: Loushin, S. K.; Liu, S.-Y.; Dykstra, C. E. *J. Chem. Phys.* **1986**, *84*, 2720.

(36) Burgi, H. B.; Dunitz, J. D.; Sheter, E. *J. Am. Chem. Soc.* **1973**, *95*, 5065. Burgi, H. B.; Dunitz, J. D. *Acc. Chem. Res.* **1983**, *16*, 153.

(37) Kitaura, K.; Morokuma, K. *Int. J. Quantum Chem.* **1976**, *10*, 325. Morokuma, K. *Acc. Chem. Res.* **1977**, *10*, 294.

(38) Kitaura, K.; Sakaki, S.; Morokuma, K. *Inorg. Chem.* **1981**, *20*, 2292.

orbitals on both fragments, and filled and vacant B orbitals are incorporated. This term may therefore be called the "donative interaction" from A to B. The term CTPLX(B→A) is, of course, completely analogous. This new decomposition[38] presents the advantage that the residual term R is generally much smaller than the term MIX in the previous scheme (this implies that MIX originates largely from CT–PL coupling,[39] with little contribution from other cross-terms). Table III summarizes the results of the calculations performed within this framework at the HF/3-21G level, and (for structure **5a**) at the HF/6-31G* level. The results obtained with the two basis sets are fairly similar. In Table III, DEF represents the energy of the individual reactant fragments in the transition state relative to the undistorted reactants.

We note from the table that the magnitude of INT is actually larger for **5b** than for **5c**, although the latter structure is lower in energy. The highly distorted acrolein fragment in **5b**, however, is 5.0 kcal/mol higher in energy than the corresponding fragment in **5c**. This is due to much more extensive structural rearrangement in the acrolein fragment in **5b** and to the decrease in conjugation caused by rotation about the central C–C bond, as discussed earlier. Some important conclusions which can be derived from this analysis are the following. First of all, the low value of INT for **5a** is largely due to the high value of the EX term, which is considerably more positive (that is, destabilizing) than EX in **5b** and **5c**. Repulsion between filled orbitals is therefore particularly significant for this four-centered transition state, as would be suggested even by simple topological arguments. Interestingly, the sum of CTPLX energy components is more negative (stabilizing) for **5a** than for **5b**. The calculations also confirm that the stabilizing electrostatic interaction is largest in **5c**, in which attack takes place on the carbonyl carbon.

A direct comparison between the energy components in **5a** and in the two other structures may not be the best way of contrasting the characteristics of the three transition states. **5a** is a "later" and thus tighter transition structure where the magnitude of all interactions (attractive and repulsive) is very large. As a consequence, both EX and CTPLX are substantially larger than in the other two structures. An earlier transition state, on the other hand, is characterized by a decrease in magnitude in the filled orbital repulsion as well as in the stabilizing interaction between filled and vacant orbitals.

In order to compare "intrinsic" contributions of various energy components among the transition structures, it is best to place the interacting fragments at the same "intermolecular separation". It has been suggested by previous studies that the intermolecular separation at which the exchange repulsion is the same among various structures provides a good basis for such a comparison.[40] We have obtained this geometry for **5a** by stretching both forming bond lengths and repeating the analysis on this new, distorted structure (**5a′** in Table III). We found that, for a 0.115-Å stretching of each bond, EX becomes equal to the value of EX in **5c** (71.6 kcal/mol). The value of ES is now 13.9 kcal/mol smaller than in **5c**, while the sum of the two CTPLX is still larger in magnitude for **5a′** (mainly due to CTPLX from methyllithium to acrolein), but only by 4.5 kcal/mol. This type of calculation thus gives a clearer indication of the relative importance of the other terms; in this case, it clearly brings out the importance of ES in favoring **5c**.

Finally, we briefly return to the question of the similarity in the energies of **5c** and **5d**, which is not predictable a priori in light of the preference for the s-trans conformer of ground-state acrolein.[31] In our opinion, this conformational bias is still present in the two early transition states, but it is counteracted by a repulsive interaction between the incoming nucleophilic methyl group and the double bond of the enal moiety. This is more significant for **5c**, since both carbons of the vinyl group are closer to the nucleophile than in **5d** (the methyl-carbon–α-carbon distances are 2.98 and 3.04 Å in **5c** and **5d**, respectively, while the methyl-carbon–β-carbon distances are 3.56 and 4.02 Å). This follows from the requirement of a larger-than-90° angle of nucleophilic attack on the C=O group,[36] which brings the nucleophile in closer contact with the group which lies anti to the carbonyl group—the C=C bond in **5c**, a mere hydrogen atom in **5d**. The destabilizing interaction also induces a torque in the vinyl group, which tends to rotate away from the methyllithium moiety. This is evident from the values calculated for the C=C—C=O dihedral angles (Figure 3), which deviate considerably from 180° and 0°. The deviation from planarity (and the ensuing loss in conjugation) is larger in **5c** (where ω(C=C—C=O) is equal to 163.6°) than in **5d** (ω(C=C—C=O) = −11.2°). This, too, contributes to the relative stabilization of **5d**. The effect is, of course, quite subtle; the energy gap between s-trans and s-cis ground-state acrolein conformers is less than 2 kcal/mol. Obviously, which type of transition structure is favored in the reaction of larger enals or enones depends on the substitution pattern of the latter. For the purpose of comparing transition states for 1,2- and 1,4-addition, however, either geometry of approach can be considered. In the next section, we will consider only the 1,2-addition of methylcopper to *s-trans*-acrolein in our discussion.

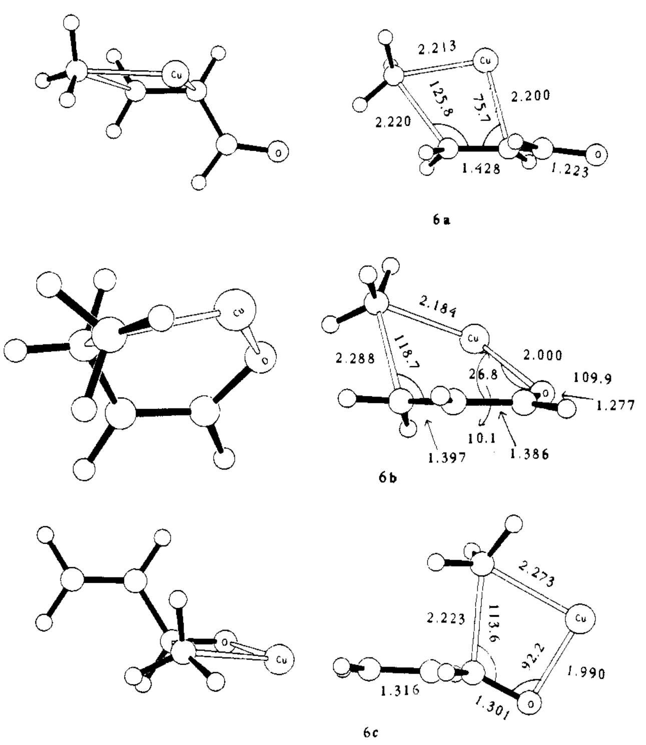

Figure 4. Transition structures (in ångstroms and degrees) for the addition of methylcopper to acrolein: (a) 1,4-addition via a four-membered transition structure: (b) 1,4-addition via a six-membered transition structure; (c) 1,2-addition.

Table IV. Activation Energies of Transition Structures **6a–c** Calculated with Reference to σ-Complex **4a**[a]

	$E_{ts\text{-}\sigma}$		
transition structure	HF/3-21G-ECP(DZ)	HF/6-31G*-ECP(DZ)	MP2/6-31G*-ECP(DZ)
6a	52.95 [53.76][b]	48.22	43.72
6b	29.39 [29.14][b]	33.84	
6c	40.57 [41.27][b]	42.22	42.58

[a] All energies are calculated on geometries optimized at the HF/3-21G-ECP(DZ) level. [b] HF/3-21G-ECP(SZ).

Transition States for the Nucleophilic Addition of Methylcopper. We shall now turn our attention to the transition structures for

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(39) This is readily understandable as follows: if charge transfer occurs from a filled orbital on fragment A to a vacant B orbital, the energy of the former is lowered and the energy of the latter is raised. This increases the gap between filled and vacant B orbitals, thus diminishing the magnitude of the polarization term PL. This accounts for the large, positive value of MIX in all cases.

(40) Sakaki, S.; Kitaura, K.; Morokuma, K. *Inorg. Chem.* **1982**, *21*, 760. Sakaki, S.; Kitaura, K.; Morokuma, K.; Oukubo, K. *Inorg. Chem.* **1983**, *22*, 104.

Table V. Total Interaction Energy (INT) and Individual Energy Components of INT in **6a–c** (in kcal/mol)[a]

transition structure	DEF_A	DEF_B	INT	ES	EX	CTPLX (A→B)	CTPLX (B→A)	R
6a	18.4	14.8	−5.2	−60.1	139.0	−24.7	−55.2	−4.2
6b	25.6	11.8	−33.0	−72.5	112.1	−12.4	−47.2	−13.0
6c	15.5	17.3	−17.2	−82.9	139.6	−25.0	−40.2	−8.7

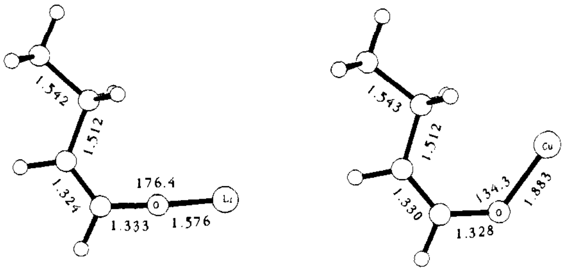
[a] Here A is the acrolein moiety, B methylcopper.

methylcopper addition, **6a–c** (Figure 4). Table IV shows the activation energies relative to σ-complex **4a** at the HF/3-21G-ECP(DZ) and HF- and MP2/6-31G*-ECP(DZ)//HF/3-21G-ECP(DZ) levels.

It is quite evident from Figures 3 and 4 that the geometric features are basically the same as for the corresponding structures **5a–c** for methyllithium. The activation energies, on the other hand, do not follow the same order: the six-membered transition structure **6b** is found to be favored over **6c** by an overwhelming 8.4 kcal/mol at the HF/6-31G*-ECP(DX)//HF/3-21G-ECP-(DZ) level. **6a** is once again disfavored, but the energy gap with respect to **6c** is only 6.0 kcal/mol. Moreover, the previous MP2/6-31G* calculations on structures **5c** and **5a** show that the correlation energy correction is about 4.4 kcal/mol higher for the latter. This consideration, and the small energy gap between **6a** and **6c**, prompted us to carry out MP2/6-31G*-ECP(DZ) calculations on these two structures. At this level, **6c** was still favored, albeit by only 1.1 kcal/mol. No post-Hartree–Fock calculations were performed on transition state **6b**. Given the large energy differences between **6b** and the other two structures at the Hartree–Fock level, higher-level computations are not expected to modify the present picture.

The methylcopper molecule is not as strongly polarized as methyllithium. The importance of purely electrostatic terms in the three transition structures is therefore diminished, and orbital symmetry control becomes dominant. The four-electron transition state **6c** is disallowed and one might therefore expect it to be disfavored with respect to **6b**, as we have indeed found. It is interesting to note that this is the case in spite of the presence of filled d orbitals on the transition metal. Conceivably, d orbitals of appropriate symmetry could be involved in stabilizing cyclic interactions with the low-lying vacant orbitals of the carbonyl group. Such a participation has been suggested for the reaction of lithium dialkylcuprates.[41-43] However, the highest molecular orbital of methylcopper is the Cu–C σ orbital, which is largely localized on the carbon atom. The next highest occupied molecular orbital is degenerate, and each in this pair has a large d character; however, these orbitals are substantially (ca. 106 kcal/mol) lower in energy than the HOMO. These are the d_{xz} and d_{yz} orbitals, taking the Cu–C bond to lie on the *z* axis. Of these, only the d_{yz} orbital has the correct symmetry to interact with the LUMO of the acrolein molecule. Subjacent orbital symmetry control,[44] therefore, should not be expected to operate in this type of reaction.

Once again, an energy decomposition analysis provides quantitative support for the arguments outlined above. The analysis was performed using the same procedure described for the transition states **5a–c**, using the 3-21G-ECP(DZ) basis set. The results are given in Table V.



7b **8b**

Figure 5. Optimized geometries (HF/3-21G and HF/3-21G-ECP(DZ)) of the lithium (**7b**) and copper (**8b**) *Z*-enolates of butanal. C_s symmetry was constrained in both cases.

We must first of all point out that all components, even electrostatic terms, are larger than for the energy decomposition analysis of **5a–c**. This is simply a consequence of the much larger number of electrons in methylcopper, as well as the "lateness" of transition states **6a–c** relative to their counterparts **5a–c**. The latter observation is confirmed by inspection of the optimized geometries of the acrolein fragments, which are always more "product-like" in **6a–c**. The forming C- -C bond lengths, on the other hand, are 0.2 Å or so shorter. This lateness is most likely related to the lower exothermicity of the reactions of methylcopper. This was shown to be true for the reactions proceeding via **5b** and **6b**, which yield the metal *Z*-enolates **7b** and **8b**[45] (Figure 5). Geometry optimization of the latter structures was performed at the HF/3-21G level. The reaction exothermicities, measured from the most stable complexes (**3a** and **4a**, respectively), were found to be equal to 43.18 kcal/mol for the formation of **7b** and 16.84 kcal/mol for the formation of **8b**. The observation of large ES values calculated for structures **6a–c**, therefore, does not invalidate our previous conclusions on the dominance of ES terms in determining the regioselectivity of the methyllithium reaction.

As shown in Table V, **6b** is an earlier transition structure than the other two. This is evident from the much smaller value of EX in **6b**, as well as from the smaller value for DEF_B (DEF_A, on the other hand, is not a good indicator of the "earliness" of the transition state because the bond reorganization in the acrolein fragment in **6b** is necessarily much more extensive than in both **6a** and **6c**; this point has already been discussed in conjunction with the analysis of the energy components in **5a–c**). The small value of EX is predictable on the basis of simple orbital symmetry arguments, and it is the leading factor which determines the preference calculated for this transition state over the other two. The value of CTPLX for the donation from methylcopper to acrolein (CTPLX(B→A)) is also larger in **6b** than in **6c**. This is not only in accord with simple frontier orbital arguments, but it is particularly noteworthy in that **6b** is an early transition state, and thus all interactions, attractive and repulsive, are expected to be smaller than in **6c**. The CTPLX(B→A) term is the only exception in this respect. A comparison between **6a** and **6c** indicates that the CTPLX(B→A) term favors the former, in accord with the notion that the LUMO of acrolein is localized mainly on the C=C bond; however, this contribution is more than compensated by the ES term which is much more stabilizing in **6c**. Nonetheless, quantitative conclusions in this particular case seem unwarranted, since higher level (MP2/6-31G*//HF/3-21G) calculations showed that the 3-21G calculations overestimate the

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(41) Corey, E. J.; Boaz, N. W. *Tetrahedron Lett.* **1984**, *25*, 3063. Corey, E. J.; Boaz, N. W. *Tetrahedron Lett.* **1985**, *26*, 6015. Smith has also interpreted the stereoselectivity observed in cuprate addition to 5-methoxycyclopentenones in terms of a nucleophilic mechanism: Smith, A. B., III, Dunlap, N. K.; Sulikowski, G. A. *Tetrahedron Lett.* **1988**, *29*, 439. Smith, A. B.; Trumper, P. K. *Tetrahedron Lett.* **1988**, *29*, 443. See also ref 33a. Strong evidence in favor of a nucleophilic mechanism for the reaction of lithium dimethylcuprate with alkyl halides has been presented by Johnson: Johnson, C. R.; Dutra, G. A. *J. Am. Chem. Soc.* **1973**, *95*, 7783. For a different postulate for the mechanism of dialkylcuprate additions, see ref 10.

(42) Preliminary calculations indicate that the HOMO of $Li(Me)_2Cu$ does have a substantial contribution from the in-plane copper d orbital: Dorigo, A. E.; Morokuma, K., manuscript in preparation.

(43) Calculations by Whangbo and co-workers suggest that the interaction between *vacant* orbitals on $(Li(Me)_2Cu)_2$ and filled orbitals on the conjugated system may determine the geometry of approach of the cuprate: Stewart, K. R.; Lever, J. R.; Whangbo, M.-H. *J. Org. Chem.* **1982**, *47*, 1472.

(44) Berson, J. A.; Salem, L. *J. Am. Chem. Soc.* **1972**, *94*, 8917.

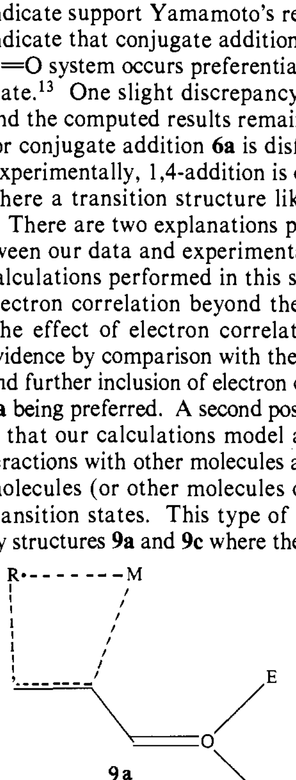
(45) From this point onward, the structures are labeled in a fashion consistent with the remainder of the text. Therefore, there are no structures **7a**, **7c**, **8a**, **8c**, **8b**, or **10b**.

stability of **6c** with respect to **6a** (Table II).

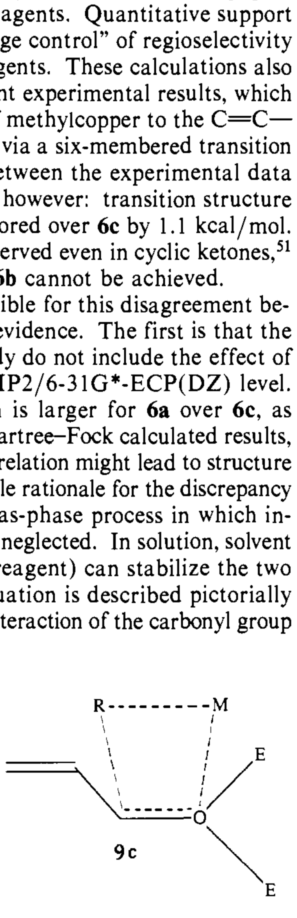
The preference for the six-membered transition state **6b** is also of note in the light of several studies which have addressed the question of the involvement of such structures in related reactions. House and co-workers pointed out that the product implied by structures such as **5b** or **6b** is a cis enolate, whereas the trans isomer was the major product in the addition of lithium dimethylcuprate to several conjugated ketones studied by the authors.[46] The results of our calculations are not incompatible with such data, however, since lithium dimethylcuprate is not simply a mixture of methylcopper and methyllithium,[47] and is believed to react via either an electron-transfer mechanism[10] or via nucleophilic attack by the d orbitals on copper.[41,42] Cyclic transition states similar to **6b** have been postulated for the reactions of organomagnesium compounds. Stereochemical evidence against their involvement, similar to that described by House,[46] has been found by Johnson.[48] Klein also favored a noncyclic mechanism,[49] but Riviere and co-workers showed that phenylmagnesium bromide adds to several enones to give an intermediate cis enolate exclusively.[50] The cis enolate was largely favored even in the presence of cuprous salts, although ketones bearing bulky substituents on the α carbon yield mostly the less hindered trans enolate.

The calculations described are in agreement with the known preference for 1,2-addition of methyllithium and for conjugate (1,4-) addition of organocopper reagents. Quantitative support is provided for the notion of "charge control" of regioselectivity in the addition of alkyllithium reagents. These calculations also indicate support Yamamoto's recent experimental results, which indicate that conjugate addition of methylcopper to the C=C—C=O system occurs preferentially via a six-membered transition state.[13] One slight discrepancy between the experimental data and the computed results remains, however: transition structure for conjugate addition **6a** is disfavored over **6c** by 1.1 kcal/mol. Experimentally, 1,4-addition is observed even in cyclic ketones,[51] where a transition structure like **6b** cannot be achieved.

There are two explanations possible for this disagreement between our data and experimental evidence. The first is that the calculations performed in this study do not include the effect of electron correlation beyond the MP2/6-31G*-ECP(DZ) level. The effect of electron correlation is larger for **6a** over **6c**, as evidence by comparison with the Hartree–Fock calculated results, and further inclusion of electron correlation might lead to structure **6a** being preferred. A second possible rationale for the discrepancy is that our calculations model a gas-phase process in which interactions with other molecules are neglected. In solution, solvent molecules (or other molecules of reagent) can stabilize the two transition states. This type of situation is described pictorially by structures **9a** and **9c** where the interaction of the carbonyl group of **6a** and **6c** with a generic electrophile E is shown. E can be either a solvent molecule or a Lewis acid, which is typically used together with the alkylcopper reagent.[4]



9a



9c

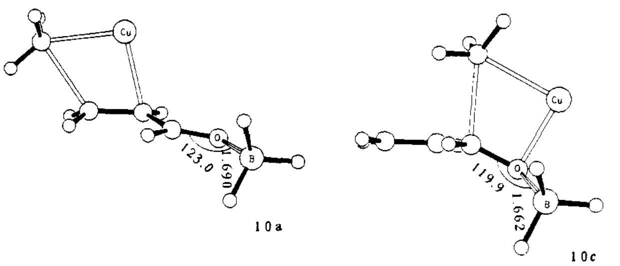


Figure 6. Partially optimized (see text) transition structures for the 1,4-addition (**10a**) and the 1,2-addition (**10c**) of methylcopper to the σ complex of *s-trans*-acrolein with borane.

We therefore decided to probe the effect of complexation of **6a** and **6c** with a molecule of borane (BH_3). This electrophile was chosen because it is a weak Lewis acid; thus, these calculations also serve to mode the conjugate addition of alkylcopper–Lewis acid complexes to C=C—C=O systems.[4,13] The energy of the –C=O- -BH_3 binding was evaluated approximately as follows. The methylcopper and acrolein fragments were "frozen" in the geometries calculated in **6a** and **6c**; geometry optimization of the BH_3 fragment in structures **10a** and **10c** (Figure 6) was then carried out. The minimal STO-3G basis set was used for the borane molecule. This is only an approximate way to evaluate the complexation energies. Nonetheless, this procedure is justified because the effect of borane on the geometry of the transition structure is expected to be small. Complexation of acrolein itself with borane causes only a small distortion in the geometry of acrolein.[52]

Our calculations were found to favor **10c** by 16.33 kcal/mol, almost 4 kcal/mol higher than the energy difference between **6a** and **6c** (12.38 kcal/mol at the HF/3-21G-ECP(DZ) level). The first molecule of borane therefore enhances the preference for 1,2-addition. The energies of structures **10a** and **10c** were recalculated at the HF/6-31G*-ECP(DZ) level, but the preference for **10c** remained large (9.38 kcal/mol) and was significantly higher than the energy gap favoring **6c** over **6a** at the same level (6.00 kcal/mol). This last result indicates that the calculated preference for **10c** over **10a** persists even with an adequate basis set, and that it is not an artifact of the STO-3G basis set used for the BH_3 fragment in the geometry optimizations. Thus, it appears that complexation at the carbonyl compound *favors* 1,2-addition.[53] An energy decomposition analysis showed that the origin of this preference is mainly due to the electrostatic component of the interaction. The donation of the oxygen lone pair causes additional polarization in the C=C—C=O π-electron system, which yields a more favorable electrostatic interaction for 1,2-addition than for 1,4-addition. It is possible that other interactions, such as ligation of the metal center,[13] are responsible for the observed preference for conjugate addition, but detailed calculations designed to test such hypotheses are beyond the present scope of this investigation.

Conclusions

Nucleophilic additions to α,β-unsaturated carbonyl compounds have been modeled by ab initio molecular orbital studies of the reaction between methylcopper and methyllithium with acrolein.

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[46] House, H. O.; Respess, W. L.; Whitesides, G. M. *J. Org. Chem.* **1966**, *31*, 3128.

[47] Detailed ^{1}H and ^{7}Li NMR investigations by Lipshutz and co-workers have shown that lithium dimethylcuprate exists as a single, discrete species in ether. For ether/tetrahydrofuran solution, methyllithium and "Me_3Cu_2Li" are also present: Lipshutz, B. H.; Kozlowski, J. A.; Breneman, C. M. *J. Am. Chem. Soc.* **1985**, *107*, 3197. See also: Bertz, S. H.; Dabbagh, G. *J. Am. Chem. Soc.* **1988**, *110*, 3668.

[48] Malhotra, S. K.; Johnson, F. *J. Am. Chem. Soc.* **1965**, *87*, 5493.

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[51] See, for example: Karpf, M.; Dreiding, A. S. *Tetrahedron Lett.* **1980**, *21*, 4569. Kende, A. S.; Roth, B.; Sanfilippo, P. J.; Blacklock, T. J. *J. Am. Chem. Soc.* **1982**, *104*, 5808. Heathcock, C. H.; Tice, C. M.; Germroth, T. C. *J. Am. Chem. Soc.* **1982**, *104*, 3081.

[52] Dorigo, A. E.; Morokuma, K., unpublished results. See also ref 31 for calculations on borane complexes with α,β-unsaturated acids and esters.

[53] Similar calculations were also performed on the complexes of **6a** and **6c** with two molecules of borane, one on in each side of the carbonyl group. These calculations represent an extreme case, since in dilute solutions a solvent molecule is likely to replace one of the coordinating Lewis acid molecules; however, this model is adequate for the purpose of probing the effect of electrophilic complexation of the oxygen atom. Once again, the methylcopper and acrolein moieties were "frozen" into the geometries of **6a** and **6c**. The energy difference between the two complexes was found to be equal to 16.77 kcal/mol in favor of the complex of **6c**. This value is even larger than the gap separating **10a** and **10c**.

Three transition structures have been located for each nucleophile. Methyllithium is calculated to favor 1,2-addition over 1,4-addition via either a four-membered or a six-membered cyclic transition structure. In the case of methylcopper, a cyclic, six-membered structure is found to be markedly preferred over the other two addition modes. These results confirm the notion that the reactions of the "hard" alkyllithium nucleophiles are charge-controlled, whereas the alkylcopper reactions are controlled by orbital interactions. Our calculations also show that conjugate addition of methylcopper to acrolein proceeds to yield directly the metal enolate, rather than the α-cuprio ketone, in agreement with recent experimental observations.

Registry No. $LiCH_3$, 917-54-4; MeCu, 1184-53-8; acrolein, 107-02-8.

The Walk Rearrangement in Bicyclo[2.1.0]pent-2-ene. An MCSCF Study

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Abstract: The walk rearrangement in bicyclo[2.1.0]pent-2-ene has been examined by ab initio calculations at Hartree–Fock, Møller–Plesset, and multiconfigurational levels of theory. At the multiconfigurational level of theory, it is found that the Woodward–Hoffman allowed reaction, occurring with inversion at the migrating carbon, is a concerted process, while that occurring with retension proceeds via a biradical intermediate. The difference in activation energies for the two reaction pathways is predicted to be at least 8 kcal/mol, favoring the Woodward–Hoffmann allowed reaction. The activation energy calculated at the MP2/6-31G* level for the reaction occurring with inversion agrees well with the value that can be estimated from experimental data. Calculations using spin contaminated unrestricted Hartree–Fock wave functions are found to give deviating results.

The migration of a divalent group, such as O, S, NR, or CR_2, which is part of a three-membered ring in a bicyclic molecule, is commonly referred to as a "walk" rearrangement.[1] The rearrangement can formally be characterized according to the Woodward–Hoffmann (W–H) rules as being a (1, *n*)-sigmatropic rearrangement.[2] Of the neutral hydrocarbon systems,[3] derivatives of the three smallest homologs, bicyclo[2.1.0]pent-2-ene, bicyclo[4.1.0]hepta-2,4-diene, and bicyclo[6.1.0]nona-2,4,6-triene, have been studied experimentally.[1a] These rearrangements can be denoted as (1,3)-, (1,5)-, and (1,7)-sigmatropic shifts. For reactions occurring in a concerted manner, i.e., without any intermediates along the reaction pathway, the W–H rules predict that the (1,3)- and (1,7)-migration should occur with inversion of the cyclopropane ring, while the (1,5)-migration should occur with retention of configuration. The walk rearrangement in the parent bicyclo[2.1.0]pent-2-ene system is not observed since the ring-opening reaction forming cyclopentadiene occurs at lower temperature. For the larger homologs the ring-open and -closed forms are in equilibrium, with the ring-open form favored in the parent systems. For systems with electron-withdrawing groups at the top position of the cyclopropane ring, such as cyano or esters, the walk rearrangement can compete with ring-opening reactions. For suitably substituted compounds belonging to the above three systems, it is found that the walk rearrangement occurs exclusively with inversion of configuration at the top carbon. For the bicyclo[4.1.0]hepta-2,4-diene system this is opposite to the prediction based on the W–H rules and is indeed one of the few known exceptions.

Recently Skancke, Yamashita, and Morokuma (SYM) reported ab initio calculations on the ring opening and walk rearrangements of the parent bicyclo[2.1.0]pent-2-ene.[4] Their conclusion was that the walk rearrangement occurs with inversion but via a biradical intermediate which was estimated to be 6 kcal/mol below the transition state leading to it. The barrier for rotation of the migrating CH_2 group in the intermediate was calculated to be 3 kcal/mol. The calculated activation energy for the walk rearrangement at the partial fourth-order Møller–Plesset level (MP4(SDQ)/6-31G*) was 41 kcal/mol (the value at the MP2/6-31G* level was 51 kcal/mol) compared to a value of 40 kcal/mol that can be estimated from experimental data.[5] In all cases they used spin unrestricted Hartree–Fock and Møller–Plesset wave functions (UHF and UMP) which for ground-state molecules are identical with spin restricted wave functions (RHF and RMP).

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(1) For a review of walk rearrangements, see: (a) Klarner, F.-G. *Topics Stereochem.* **1984**, *15*, 1. (b) Childs, R. F. *Tetrahedron* **1982**, *38*, 567.

(2) Woodward, R. B.; Hoffmann, R. *Angew. Chem., Int. Ed. Engl.* **1969**, *8*, 781.

(3) For calculations related to similar cationic systems, see: (a) Hehre, W. J. *J. Am. Chem. Soc.* **1972**, *94*, 8908. (b) Devaquet, A. J. P.; Hehre, W. J. *J. Am. Chem. Soc.* **1974**, *96*, 3644. (c) Hehre, W. J. *J. Am. Chem. Soc.* **1974**, *96*, 5207. (d) Hehre, W. J.; Devaquet, A. J. P. *J. Am. Chem. Soc.* **1976**, *98*, 4370.

(4) Skancke, P. N.; Yamashita, K.; Morokuma, K. *J. Am. Chem. Soc.* **1987**, *109*, 4157.

(5) The activation energy for the walk rearrangement in bicyclo[2.1.0]pent-2-ene is estimated as follows. A lower bound of 28 kcal/mol for the activation energy ($\Delta G^{\ddagger}$) can be determined from the parent system since the activation energy for the ring-opening reaction is 24.9 kcal/mol, and none of the product expected from a walk rearrangement is observed (assuming a 1% detection limit, which corresponds to 3 kcal/mol at the reaction temperature).[6] The activation energy for the walk rearrangement in the substituted system 5-cyano-1,5-dimethylbicyclo[2.1.0]pent-2-ene is 21.9 kcal/mol.[7] To correct for the effects of a cyano and a methyl group, we utilize data taken from the interconversion of cis and trans isomers of cyclopropanes. For this presumably similar reaction the stabilizing effect of a cyano group is found to be 8.9 ± 1.0 kcal/mol, while that of a CH_3 group is 2.0 kcal/mol.[8] Assuming similar effects for the walk rearrangement we have $\Delta G^{\ddagger}_{\mathrm{est}} \simeq 21.9 + 8.9 + 2.0 \cong 35$ kcal/mol. To make comparison with the calculated values in Table VI, we have to correct for the entropic contribution to $\Delta G^{\ddagger}$ and for vibrational contributions to $\Delta H^{\ddagger}$. $\Delta S^{\ddagger}$ for the reaction is probably slightly positive (the calculated value using the CAS1/STO-3G frequencies is 5.8 cal/mol·K, and the experimental value for cis–trans isomerization in 1,2-dicyanocyclopropane is 6.6 cal/mol·K) and $\Delta H^{\ddagger}$ is consequently $\simeq$2 kcal/mol higher than $\Delta G^{\ddagger}$. The correction for zero-point energy differences is typically 2–3 kcal/mol (the calculated value here is 3.4 kcal/mol), thus the final estimate of $\Delta H^{\ddagger}$ to be directly compared to the calculated values is $\cong$40 kcal/mol. To estimate the energy difference between reaction occurring with inversion and retention we note that in 5-cyano-1,5-dimethylbicyclo[2.1.0]pent-2-ene only the reaction taking place with inversion is observed, thus the energy difference in this compound must be >3 kcal/mol (again assuming a 1% detection limit).[7] Since the cyano and methyl groups probably stabilize preferentially the reaction occurring with retention, the 3 kcal/mol lower bound should also hold for the parent bicyclo[2.1.0]pent-2-ene.

0002-7863/89/1511-4643$01.50/0