Experimental and Computational Studies of Nucleophilic Additions of Metal Hydrides and Organometallics to Hindered Cyclohexanones

Kaori Ando,[1,†] K. N. Houk,*[,†] Joachim Busch,[‡] Alexander Menassé,[‡] and Urs Séquin*[,‡]

Department of Chemistry and Biochemistry, University of California, Los Angeles, California 90095-1569, and Institut für Organische Chemie der Universität Basel St. Johanns-Ring 19, CH-4056 Basel, Switzerland

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The stereochemistries of nucleophilic additions of several hydride, methyl, and acetylenic Grignard and lithium reagents to hindered cyclohexanones were investigated experimentally. Acetylenic reagents attack hindered cyclohexanones from the axial direction, in contrast to the result with other reagents. Ab initio calculations and a modified MM2 transition-state force field were used to study the origins of stereoselectivity.

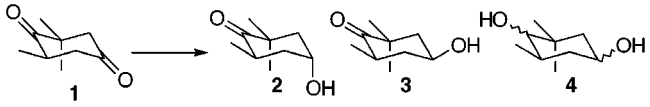
Introduction

The stereoselectivities of metal hydride reductions and organometallic additions to cyclohexanones are well-established. Small nucleophiles attack unhindered cyclohexanones from the axial direction, while steric hindrance leads to equatorial attack. The origins of these phenomena have been debated and reviewed.[2] We have investigated the special case of nucleophilic attack on highly sterically congested cyclohexanones, with a particular emphasis on understanding why acetylenic reagents attack preferentially from the axial direction, in contrast to the well-accepted generalization noted above. We report several new experimental results, compare them with literature data, and report calculations with both quantum-mechanical and force-field methods which help explain the origins of these stereoselectivities.

Recently, there was a report of high stereoselectivity for axial attack in the additions of an acetylenic lithium reagent to a sterically hindered cyclohexanone.[3] We have found that other reagents give low selectivities, with a preference for equatorial attack in the addition of the other organolithium and Grignard reagents to the same cyclohexanone. We report here these results, along with force-field and quantum-mechanical modeling of nucleophilic additions of acetylenic nucleophiles, and provide a rationale for the observed selectivities.

We previously studied the stereoselectivities of nucleophilic additions to carbonyl compounds computationally.[4−6]

Scheme 1



We developed special substructures for Allinger's MM2 force field based on ab initio calculations that reproduce the stereoselectivities. Nucleophilic additions to carbonyl compounds might be expected to be difficult to model because of the influence of metal cation coordination and solvation on the stereochemistry. Nevertheless, rather simple force-field and steric congestion models are surprisingly successful in accounting for the stereochemistries of hydride reductions.[4,5] A general review of these methods has established the utility in understanding the origins of stereoselectivity.[5,6] Here, we extend these models to the nucleophilic additions of organometallics to hindered cyclohexanones.

Results and Discussion

Experimental Metal Hydride and Organometallic Reactions. The regio- and stereoselectivities of the reduction of (*R*)-2,6,6-trimethyl-1,4-cyclohexanedione (**1**) with a number of reducing reagents have been studied experimentally (Scheme 1). The results are summarized in Table 1. Both the regio- and stereoselectivity can be controlled by choosing the appropriate reducing reagent and reaction conditions. In general, the formation of the axial alcohol **2** was preferred at −78 °C, while the equatorial alcohol **3** increased in amount at room temperature. Thus, there is a small enthalpic preference for equatorial attack, which is generally found for sterically hindered cyclohexanones.[2] This contrasts with the established behavior of 4-*tert*-butylcyclohexanone, which gives mainly **6**, the result of axial attack (Scheme 2).

The course of the nucleophilic attack by organometallic reagents at the hindered carbonyl group was also studied.

† University of California.

‡ Universität Basel.

(1) Permanent address: College of Education, University of the Ryukyus, Nishihara-cho, Okinawa 903-01, Japan.

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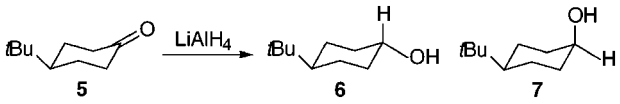
Table 1. Stereoselectivities and Regioselectivities in the Reductions of 1

reagent	*T* (°C)	time	solvent	**2**:**3**	% diols (**4**)	% educt (**1**)
iBu_3Al	−78	30 min	toluene	6:1	8	17
	rt	2 d	toluene	5:4	9	18
iBu_3Al-pyrrole	−78	30 min	toluene	3:1	0	86
	rt	3 d	toluene	1:1	3	36
$LiAlH_4$-methylephedrine	−78	30 min	ether	5:1	0	73
	rt	3 d	ether	5:1	0	75
Li(siamyl)$_3$BH	−78	30 min	THF	5:1	0	32
	rt	3 d	THF	1:3	2	7
Li(*s*-Bu)$_3$BH	−78	30 min	THF	3:1	0	12
	rt	3 d	THF	1:11	7	4
$LiB(C_2H_5)_3H$	−78	30 min	THF	1:2	14	53
	rt	3 d	THF	1:4	13	20
$LiAlH(O\text{-}tBu)_3$	−78	30 min	THF	20:1	9	65
	rt	3 d	THF	30:1	11	50
H_2/Raney-Ni (W2)	rt	1 h	MeOH	4:1	0	0
	rt	15 h	MeOH	4:1	8	0

Scheme 2



Scheme 3

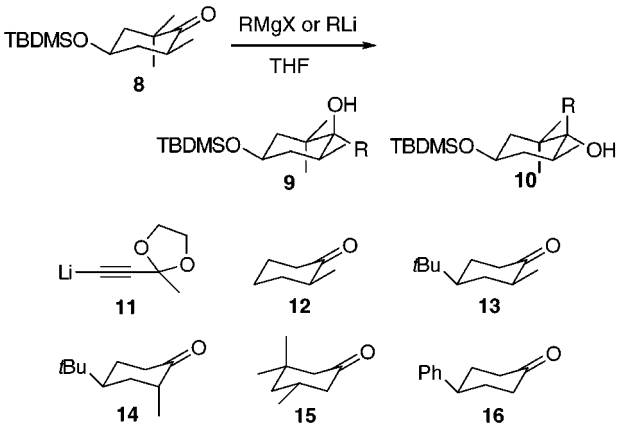


Table 2. Stereoselectivities of Nucleophilic Additions to the Hindered Cyclohexanone 8

reagent	*T* (°C)	**9**:**10**
11	−78	0:100
$H_2C{=}CHMgCl$	−78	71:29
CH_3MgBr	−78	62:38
n-C_4H_9MgCl	−78	60:40
n-C_4H_9Li	−78	60:40

The additions of various acetylenic organometallics to 2,6,6-trimethylcyclohexanone systems yield, as a result of axial attack, predominantly equatorial alcohols.[3] We have studied the additions of organolithium and Girgnard reagents to (4*R*,6*S*)-4-[(*tert*-butyldimethylsilyl)oxy]-2,2,6-trimethylcyclohexanone (**8**) (Scheme 3). While the acetylenic reagent **11** adds exclusively from the axial direction, low selectivities for equatorial attack were observed with vinyl, methyl, and *n*-butyl Grignard reagents and with *n*-butyllithium (Table 2) These experimental selectivities have been rationalized previously using molecular electrostatic potentials.[7]

Ab Initio Transition Structure for Lithium Acetylide Addition. The transition structure for the reaction of lithium acetylide with acetone was located with RHF calculations and the 6-31G* basis set incorporated in Gaussian 94[8] (Figure 1). A vibrational frequency calculation gave one imaginary frequency and confirmed that the structure is an authentic transition structure. This transition structure is unexpectedly different from the one for methyllithium addition. Judging from the forming bond distances, the transition structure for MeLi (Figure 2)[10] lies very early along the reaction coordinate, whereas the structure for HC≡CLi lies rather late. Also, the incoming acetylenic anion is leaning somewhat toward the oxygen (the bond angle C(carbonyl)−C≡C is 157°).[9] We also located the transition structures for the reaction of lithium acetylide with cyclohexanone and with two dimethyl ether molecules to mimic solvent (RHF/3-21G) (Figure 3). In both cases, the axial attack is preferred by about 1 kcal/mol, which corresponds to ~95:5 product ratio at −78 °C (for experimental data, see **5** with ethynyl Grignard reagent in Table 5). In the

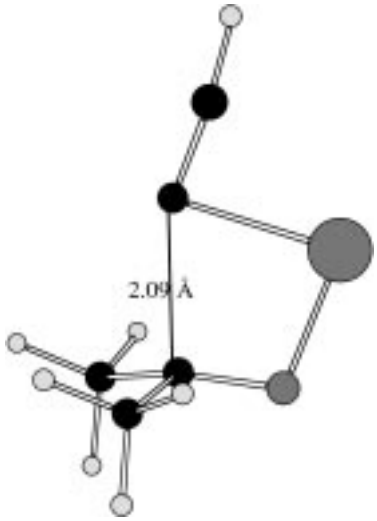


Figure 1. Acetone−lithium acetylide transition structure optimized by (RHF/6-31G*).

(7) Busch, J.; Keserü, G. M.; Kovári, Z.; Séquin, U. *Struct. Chem.* **1997**, *8*, 257−261.

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(9) RHF/3-21G computational result: the forming bond length is 2.200 Å and the bond angle C(carbonyl)−C≡C is 158.0°.

(10) Kaufmann, E.; Schleyer, P. v. R.; Houk, K. N.; Wu, Y.-D. *J. Am. Chem. Soc.* **1985**, *107*, 7, 5560−5562.

Table 3. Predicted Stereoselectivities for Hydride Addition of Cyclohexanone 1 and 5

ΔE (TS)	ratio (T (°C))	ΔE (product)	ratio (T (°C))
0.57 kcal/mol (**B**−**A**)	**2**:**3** = 4.4:1 (−78)	0.40 kcal/mol (**2**−**3**)	**2**:**3** = 1:2.0 (rt)
1.17 kcal/mol (eq−ax)	**6**:**7** = 90:10 (0)	0.53 kcal/mol (**7**−**6**)	**6**:**7** = 74:26 (0)

Table 4. Predicted Ratios of Axial and Equatorial Attack as a Function of the Forming Bond Distance

CH_3^- attack			$HC{\equiv}C^-$ attack		
C···C (Å)	ΔE (ax−eq) (kcal/mol)	**9**:**10**	C···C (Å)	ΔE (eq−ax) (kcal/mol)	**9**:**10**
2.035	1.08	94:6	2.035	0.43	25:75
2.335	0.70	86:14	2.535	0.86	10:90
2.535	0.46	77:23	2.735	1.01	7:93
2.735	0.22	64:36	2.935	1.13	5:95
2.935	−0.02	49:51	3.135	1.24	4:96

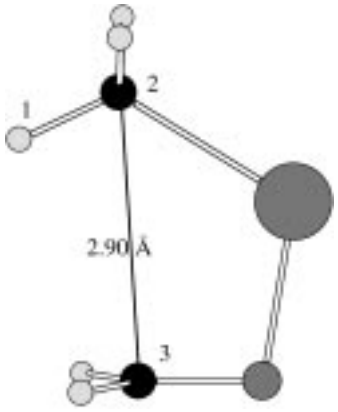

Figure 2. Formaldehyde−methyllithium transition structure optimized by RHF/3-21G.[4]

presence of dimethyl ether, the transition structures look similar to the MM2/TS geometries described later. Calculations were also performed on LiC≡CH additions to sterically hindered 2,2,6-trimethylcyclohexanone (Figure 4). Axial attack is favored with this sterically unhindered species.

Transition-State Modeling with MM2. To better understand these stereoselectivities, ab initio calculations were performed on model transition states. The energies of both transition structures for the axial and equatorial addition of hydride were calculated with our special substructures combined with the MM2 force field (MM2/TS for short),[4e] which was developed from the ab initio transition structure of the LiH−acetone reaction.[4a] The coordination of the metal to the carbonyl oxygen is an important factor, but the metal cation is not intimately involved with the bonding at the carbonyl carbon and was neglected in our computational model. This was shown to be a reasonable approximation in earlier studies.[4a] The force-field calculations reported here were carried out with the MacroModel v. 4.5 program.[11]

The results of the calculations on **1** and *tert*-butylcyclohexanone (**5**) are shown in Table 3 and Figure 5. The equatorial transition structure **A** leading to axial alcohol **2** is more stable than the axial transition structure **B** leading to **3** by 0.57 kcal/mol, which corresponds to a product ratio, **2**:**3**, equal to 4.4:1 at −78 °C, assuming equal entropies of activation. All kinetic product ratios described here are calculated from the equation $k_1/k_2 = e^{-\Delta E(\text{calcd})/RT}$, where ΔE(calcd) is the difference between the energy calculated for the two transition states, assuming equal activation entropies. An axial methyl group at the 3-position makes equatorial attack favored due to the 1,3-diaxial repulsion upon the axial attack. In the absence of steric hindrance, the axial transition structure is preferred. For example, the $LiAlH_4$ reduction of **5** shows 88−91% selectivity for the equatorial alcohol **6** experimentally[12] (Scheme 2), and 90% selectivity for the axial transition structure (leading to the equatorial alcohol) was predicted by the MM2/TS force field. On the other hand, the stability of the products is different. The equatorial alcohol **3** is calculated to be more stable than the axial alcohol **2** by 0.40 kcal/mol. As some of the reducing reagents are Lewis acids or Lewis bases, a certain amount of epimerization might occur during the reaction. An epimerization of **2** to **3** was achieved to the extent of 80% with concentrated hydrochloric acid. Thus, the formation of the axial alcohol **2** is favored kinetically, whereas the formation of the equatorial alcohol **3** is favored thermodynamically. Except for the results with $LiAlH(O\text{-}t\text{-}Bu)_3$ and $Li(s\text{-}Bu)_3BH$, the experimental results are nicely explained by the calculations. The stereoselectivity for $LiAlH(O\text{-}t\text{-}Bu)_3$ is considerably higher than predicted from the $LiAlH_4$ reduction model. The reversal of the major product under thermodynamic conditions with $Li(s\text{-}Bu)_3BH$ agrees qualitatively with experiment, although the thermodynamic preference for **3** is higher than predicted. $LiB(C_2H_5)_3H$ gives **3** predominantly under all conditions. This may be due to product isomerization, a postulate that will be tested experimentally.

Organoalkyne Addition Force Field. The MM2 force field has been extended for acetylide anion additions. The parameters for hydride addition[4e] were used, where H was replaced by C≡C−X (X = H, CH_3). For the rest of the parameters, the default MM2 values were used. As we had already developed an MM2 force field for methyl anion addition to carbonyl compounds,[4a] we compared the calculated results for methyl and acetylide addition. The MM2/TS force field predicts that the equatorial and axial attack transition structures for the methyl and acetylide anion addition differ in energy by 1.08 and −0.43 kcal/mol, implying that the ratio of **9**:**10** should be 94:6 and 25:75 at −78 °C for these two reactions. The MM2/TS predicts the correct direction of attack, although the results do not agree quantitatively with experiment. The energy difference between the two transition structures was computed with different values of the forming bond length. The results are summarized in Table 4. From these results, the distance of the forming bond in the transition structure should be ∼2.7

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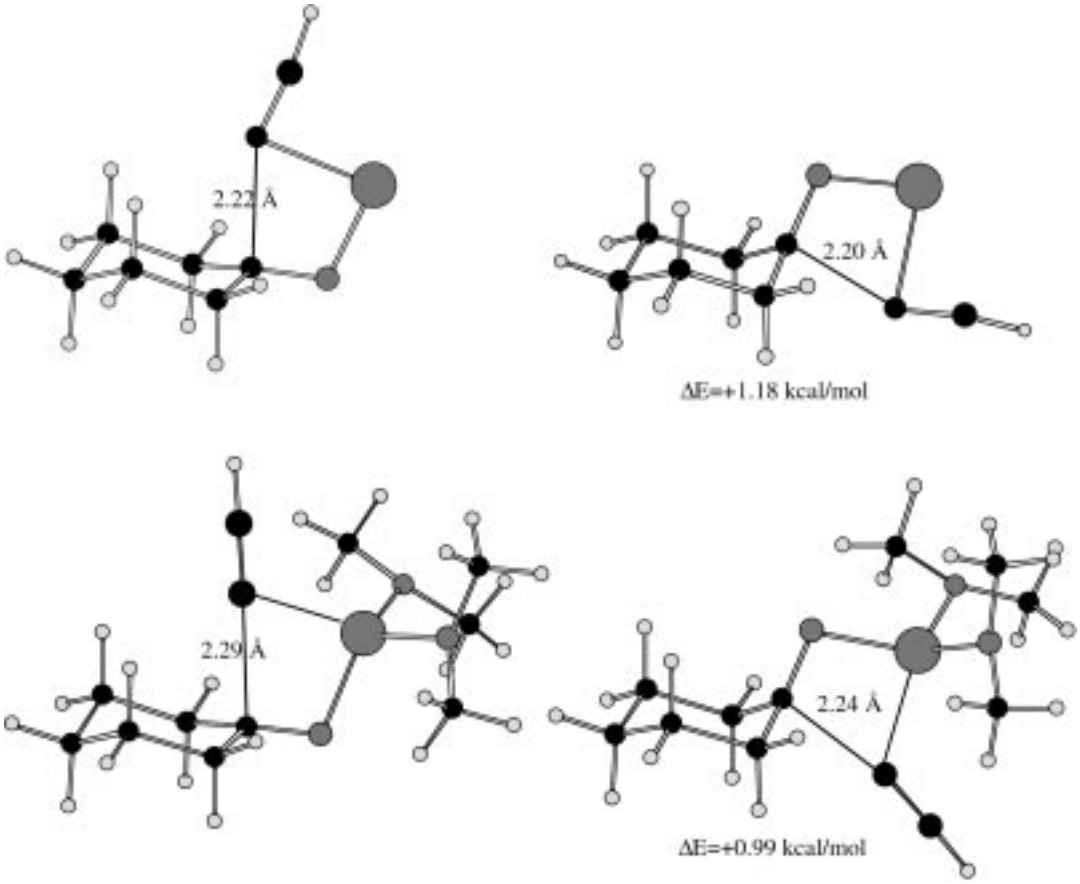

Figure 3. (Top) cyclohexanone−lithium acetylide transition structures. (Bottom) cyclohexanone−lithium acetylide transition structures with two dimethyl ether solvent molecules (RHF/3-21G).

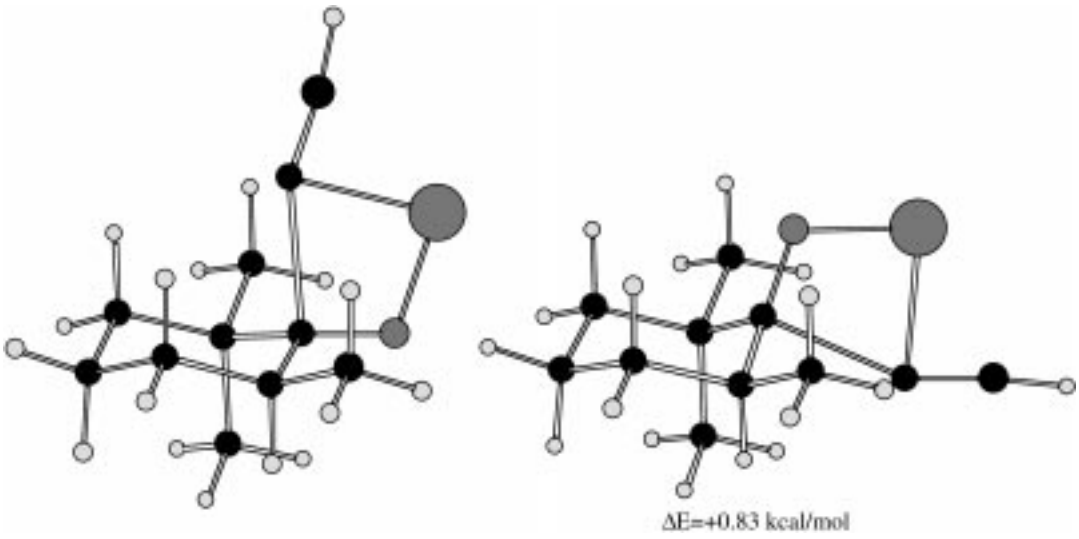

Figure 4. Trimethylcyclohexanone−lithium acetylide transition structures (RHF/3-21G).

Å. Since 2.66 Å was used previously for the forming C···C bond length in the metalated keteniminate addition transition structure,[5] the forming bond distance was set to 2.66 Å.

A torsional constant was also varied in the methyl anion case. The V_1 torsional parameter for dihedral angle H(1)−C(2)−C(3)═O is set to 10.0 mdyn/deg in the calculations reported here. This fixes the metal-coordinated four-center transition structure. When this parameter was set at 1.0 mdyn/deg (the original value),[4] the dihedral angle for the axial transition structure of **15** turns out to be 129° in order to minimize the steric hindrance between the incoming nucleophile and the 3-axial methyl group. The larger torsional angle is needed to maintain the shape of the transition state in sterically hindered cases. The result is a model that can be used to compare stereoisomeric transition states.

Comparisons of Calculations and Experiment for Organometallic Additions. The modified MM2/TS force field correctly predicts the observed stereoselectivities for the nucleophilic addition of organometallics to several cyclohexanones. Table 5 shows a comparison of

Table 5. Stereoselectivities of Nucleophilic Additions to Cyclohexanones[a]

substrate	reagent	condns (solvent, *T* (°C))	isomer ratio[b] exptl	isomer ratio[b] calcd	ref
8	CH_3MgBr	THF, −78	62:38	60:40	
8	**11**	THF, −78	0:100	8:92[c]	
5	CH_3MgBr	ether, 0	58:42	54:46	13
5	CH_3Li	ether, 0	65:35		13
5	HC≡CMgBr	THF, −78	11:89	8:92	14
5	HC≡C$SiMe_3$, TBAF	THF, 18	7:93	17:83	14
12	CH_3MgI	ether, 0	84:16	83:17	15
12	HC≡CLi	THF, 25	42:58	37:63	16
12	HC≡CMgBr	THF, 25	45:55		16
13	CH_3MgI	ether, 0	83:17	80:20	15
14	CH_3MgI	ether, 0	20:80	14:86	15
15	CH_3MgI	ether, 25	100:0	≥99:1	17
15	HC≡CMgBr	THF, 0	100:0	95:5	17
16	CH_3MgI	THF, −78	55:45	55:45	4
16	CH_3C≡CLi	THF, 25	11:89	15:85	18

[a] All calculations are reported here for the first time, while the experimental entries in rows 3−15 are from the indicated references. [b] Ax-alcohol:eq-alcohol. [c] Calculation was performed as an attack of ^-C≡CH.

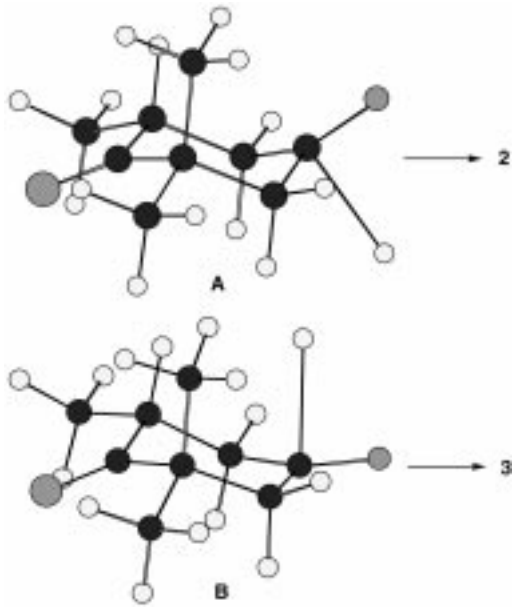

Figure 5. Favored transition states for the hydride reduction of (*R*)-2,6,6-trimethyl-1,4-cyclohexanedione (**1**) based on the MM2 transition-state model.

our computational predictions and experimental results for the cyclohexanone **8** and various alkyl-substituted cyclohexanones with methyl and acetylenic metal reagents. The MM2/TS structures for the reaction of **5** with CH_3^- and HC≡C^- are shown in Figure 6. As Felkin proposed,[13] the stereoselectivity of nucleophilic additions to cyclohexanones are influenced by two factors: (1) the steric interaction of the incoming group with the 3,5-axial substituents and (2) the torsional strain of the incoming group with the 2,6-axial substituents.[14] Large reagents (Me, vinyl, *n*-butyl) approaching from the axial side should experience significant steric interaction with both the 3,5-axial hydrogens or substituents and therefore will prefer to attack from the equatorial side. On the other hand, small reagents should encounter little interaction upon axial approach but will encounter significant tor-

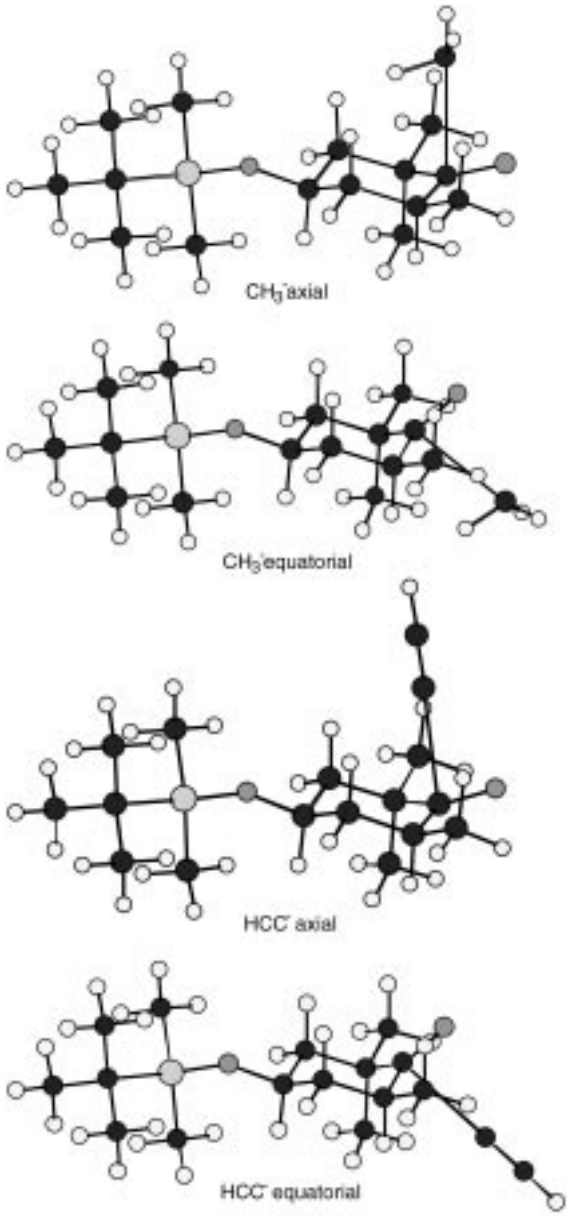

Figure 6. Favored transition structures for the nucleophilic addition of CH_3^- and HC≡C^- to (4*R*,6*S*)-4-(*tert*-butyldimethylsiloxy)-2,2,6-trimethylcyclohexanone (**8**) based on the modification of the Wu−Houk MM2 parameters.

(13) Cherest M.; Felkin, H.; Prudent, N. *Tetrahedron Lett.* **1968**, 2199−2204. Cherest, M.; Felkin H. *Tetrahedron Lett.* **1968**, 2205−2208.

(14) For a review: Ashby, E. C.; Laemmle, J. T. *Chem. Rev.* **1975**, *75*, 521−546.

sional strain from the 2,6-hydrogens or substituents upon equatorial attack; therefore, attack from the axial side is preferred. Since the acetylide anion is linear, axial attack is preferred in order to minimize torsional repulsion in the absence of steric hindrance. In the case of compound **12**, the 2-equatorial methyl group introduces a pseudoaxial hydrogen into the molecule, which increases hindrance to attack from the axial side. Good selectivity for the axial alcohol was observed for the methyl reagent, while low selectivity for the equatorial alcohol was reported for the acetylide reagent. In the case of **8**, this 2-equatorial methyl effect offsets the effect of the 2-axial methyl group. The effect of the 2-axial methyl group can be seen from the result of **14**, which gave the equatorial alcohol even in the reaction with the methyl Grignard reagent, as well.

Conclusion. We have reported several new examples of stereoselectivities in nucleophilic additions to hindered cyclohexanones. In all cases, the modified special substructures for MM2 force field gives excellent semiquantitative agreement with experimental stereoselectivities. The results can be understood by a combination of torsional and steric effects.

Experimental Section

General Methods. MPLC: silica gel 60 (15−25 μm); hexane/diethyl ether gradient. GC: 5% phenyl methyl silicone or Carbowax 20M; 110 °C, rate 5 °C/min to 270 °C. ^{1}H NMR and ^{13}C NMR: 300 and 75 MHz, respectively; chemical shifts in δ (ppm) relative to internal TMS (= 0 ppm) in $CDCl_3$, coupling constants J in Hz. GC/MS: 5% phenyl methyl silicone. Melting points are uncorrected.

Reagents. All reagents were purchased from Aldrich or Fluka and used without further purification unless specified otherwise. Reaction solvents were purified according to standard procedures. Raney nickel (W2) was prepared according to the usual method. All reactions except the Raney nickel reduction were performed under an atmosphere of argon in oven-dried glassware. (4*R*,6*S*)-4-(*tert*-Butyldimethylsiloxy)-2,2,6-trimethylcyclohexanone (**8**) was prepared according to the method of Lamb and Abrams.[2]

2-Ethynyl-2-methyl-1,3-dioxolane. A mixture of 8.714 g (0.128 mol) of 3-butyn-2-one, 44.69 g (0.720 mol) of ethylene glycol, 2.52 g (13.0 mmol) of *p*-toluenesulfonic acid monohydrate, and 28.5 g (0.210 mol) of finely ground anhydrous calcium sulfate $CaSO_4$ was stirred at room temperature for 20 h. Diethyl ether (35 mL) was then added, and the mixture was allowed to stir for an additional 10 min. Water (70 mL) was added, and the mixture was stirred again for 10 min. The phases were separated, and the aqueous layer was washed with diethyl ether (3 × 35 mL). The combined ether layers were dried over Na_2SO_4, filtered, and evaporated. The product was distilled at 44 °C/38 mbar. Yield: 8.920 g of **17** (62.1%), colorless liquid. IR (NaCl): 3277; 2113; 1176; 1031; 948; 662 cm^{-1}. ^{1}H NMR: 4.06 (m, $-O(CH_2)_2O-$); 2.49 (s, ≡CH); 1.71 (s, CH_3). ^{13}C NMR: 100.3 (OCO); 82.0 (≡C−); 70.9 (H−C≡); 64.5 (ethylenedioxy); 26.1 (CH_3). GC/EIMS (70 eV): 111 (1, $[M - H]^+$); 97 (72); 87 (4); 82 (2); 69 (8); 56 (53); 53 (100); 43 (64). Anal. Calcd for $C_6H_8O_2$ (112.13): C, 64.27; H, 7.19; O, 28.54. Found: C, 64.28; H, 7.07; O, 28.52. Lithiation was carried out in the usual way with *n*-BuLi at −78 °C for 1 h.

Stereo- and Regioselective Reduction of Diketone 1 (General Procedure). (6*R*)-2,2,6-Trimethyl-1,4-cyclohexanedione (**1**) (154.2 mg, 1.00 mmol) was dissolved in 10 mL of toluene, diethyl ether, or THF and cooled to −78 °C. Reducing agent (1 mmol) in solution was added. After 30 min of reaction, the cooling bath was removed and the reaction mixture was allowed to warm to room temperature. The reaction was continued for 2−3 days. The reaction was monitored by GC.

The reduction with *i*-Bu_3Al−pyrrole was carried out according to the method of Suzuki *et al.*[21] and $LiAlH_4$−(−)-*N*-methylephedrin reduction according to Terashima *et al.*[22]

Stereo- and Regioselective Reduction of Diketone 1 with Raney−Ni (W2). (6*R*)-2,2,6-Trimethyl-1,4-cyclohexanedione (**1**) (11.73 g, 76.07 mmol) was dissolved in 80 mL of methanol. A suspension of freshly prepared Raney-Ni (from 23.49 g of Raney-Ni alloy) was added. The flask was connected to a hydration apparatus and was shaken for 1 h under hydrogen atmosphere. The suspension was filtered over Celite, and the diastereomeric ratio was determined by GC. Purification and separation of the diastereomers were carried out by MPLC. The experimental data of the hydroxy ketones **2** and **3** were identical with those in the literature.[3]

Nucleophilic Addition at the Hindered Cyclohexanone 8 (General Procedure): Approximately 400 mg (1.48 mmol) of (4*R*,6*S*)-4-(*tert*-butyldimethylsiloxy)-2,2,6-trimethylcyclohexanone (**8**) was dissolved in 25 mL of dry THF and cooled to −78 °C. The organometallic reagents (2 equiv) were added as a solution in hexane, THF, or diethyl ether. After 2 h of reaction at −78 °C, the reaction mixture was allowed to warm to 0 °C and quenched with 12 mL of saturated NH_4Cl solution. The phases were separated, and the aqueous layer was washed twice with 10 mL of diethyl ether. The combined organic layers were dried and evaporated. The diastereomeric ratios were determined by GC. Purification and separation of the diastereomers were carried out by MPLC.

(1*R*,4*R*,6*S*)-4-[4-(*tert*-Butyldimethylsiloxy)-1-hydroxy-2,2,6-trimethylcyclohexyl]-2,2-(ethylenedioxy)-3-butyne (10a). Yield: 212 mg of **10a** (38%), colorless crystals. Mp: 94.5−94.7 °C. $[\alpha]^{25}_D$: +15.0 (c = 0.41, $CHCl_3$). IR (KBr): 3500−3250 (OH, ≡CH); 2957, 2929, 2886, 2856 (CH); 2346; 2241 (C≡C); 1473; 1460; 1378; 1359; 1249, 1199, 1182; 1100, 1078, 1037 (COC); 860; 834; 774; 687; 668 cm^{-1}. ^{1}H NMR: 4.07 (m, $-O(CH_2)_2O-$); 3.82 (m, HC(4′)); 1.93 (m, HC(6′)); 1.73 (s, CH_3-(1)); 1.85−1.26 (m, CH_2(5′), CH_2(3′), OH); 1.09 (s, CH_{3ax}-C(2′)); 1.04 (d, J = 6.5 Hz, CH_{3eq}-C(6′)); 1.00 (s, CH_{3eq}-C(2′)); 0.88 (s, CH_3(*tert*-butyl)); 0.05 (s, CH_3Si). ^{13}C NMR: 100.7 (C(2)); 86,1 (C(3)); 82.8 (C(4)); 77.6 (C(1′)); 66.7 (C(4′)); 64.5 (ethylenedioxy); 47.2 (C(3′)); 42.0 (C(5′)); 39.7 (C(2′)); 35.8 (C(6′)); 27.0 (C(1)); 26.2 (CH_{3ax}-C(2′)); 25.9 (CH_3-(*tert*-butyl)); 20.8 (CH_{3eq}-C(2′)); 18.2 (CSi); 16.5 (CH_3-C(6′)); −4.6 (CH_3Si). EIMS (70 eV): 367 (2, $[M - CH_3]^+$); 325 (12); 263 (6); 253 (1); 225 (7); 207 (15); 171 (12); 161 (18); 125 (16); 119 (27); 87 (85); 75 (100); 43 (74). Anal. Calcd for $C_{21}H_{38}O_4$-Si (382.62): C, 65.92; H, 10.01. Found: C, 66.04; H, 9.70.

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Supporting Information Available: Complete list of MM2 parameters for the nucleophilic addition force field and the Cartesian coordinates for ab initio structures given in Figures 1−4 (10 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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