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Reaction Profiles and Substituent Effects for the Reduction of Carbonyl Compounds with Monomer and Dimer Simple Metal Hydride Reagents

Takako Kudo,*,[†] Takanori Higashide,[†] Sachiyo Ikedate,[†] and Hiroshi Yamataka*,[‡]

Department of Fundamental Studies, Faculty of Engineering, Gunma University, Kiryu 376-8515, Japan, and Department of Chemistry, Rikkyo University, Nishi-Ikebukuro, Toshima-ku, Tokyo 171-8501, Japan

tkudo@sci.gunma-u.ac.jp; yamataka@rikkyo.ac.jp

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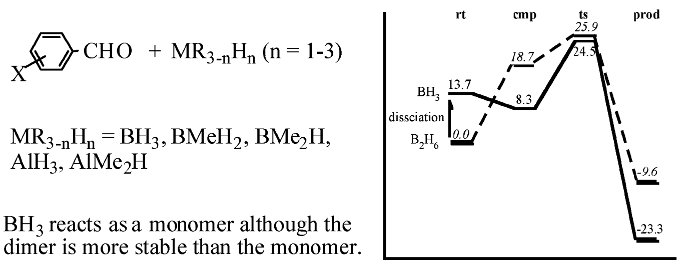

BH_3 reacts as a monomer although the dimer is more stable than the monomer.

Reaction profiles and energetics for the reactions of substituted benzaldehydes with a series of different simple metal hydrides (BH_3, $BMeH_2$, BMe_2H, AlH_3, and $AlMe_2H$) are examined computationally. B3LYP/6-31G* optimizations and MP2/6-311G* single point energy calculations revealed that the Al reagents are more reactive than B reagents. Replacement of H with Me on BH_3 or AlH_3 makes the reduction transition state (TS) less stable. Accordingly the overall reactivity is in the order $AlH_3 > AlMe_2H > BH_3 > BMe_2H$. The Hammett ρ value for substituted benzaldehydes (BAs) is negative for the initial complex formation and positive for the hydride-transfer step. The size and the sign of the apparent ρ value depend on the relative stabilities of the separated reactants and the complex. The TS structures vary according to the Hammond postulate for substituted BAs and the variation is reflected in carbonyl-carbon and aldehyde-deuterium isotope effects. Comparison of the reaction profiles of the monomer and dimer reagents reveals that the real reacting species is the monomer in the gas phase for BH_3 but the dimer for BMe_2H.

Introduction

The reduction of aldehydes and ketones is one of the most fundamental reactions of organic chemistry. Metal hydrides are common reducing reagents for such a reaction in an organic laboratory, and the reaction mechanism has been studied extensively.[1] Simple metal hydrides such as BH_3 and AlH_3 are interesting chemical species in that they are a Lewis acid and therefore electrophilic at the metal center while the hydrogens are nucleophilic, and therefore the reactions could be either electrophilic or nucleophilic.

The mechanism of the reactions of benzophenone with four simple metal hydride reagents has been examined experimentally, and the results reported are summarized as follows: (1) Hammett ρ values for the reactions of substituted benzophenones with BH_3/Et_2O, 9-borabicyclo[3,3,1]nanone (9-BBN)/THF, AlH_3/Et_2O, and diisobutylaluminun hydride (DIBAL-H)/hexane were −0.12, −0.76, 1.03, and 0.47 at 25 °C, and (2) carbonyl carbon-14 kinetic isotope effects (KIE, k^{12}/k^{14}) were 1.035, 1.027, 1.021, and 1.000, respectively.[2] The Hammett plots showed that the electronic effects on the reaction rates vary depending on the reagents; the balance of electrophilic and nucleophilic attacks by the metal atom and the hydrogen atom differs for these reagents. The carbonyl carbon KIEs showed that the nature of the transition state (TS) is basically the same for BH_3, 9-BBN, and AlH_3, but it is different for DIBAL-H. The normal (larger than unity) carbon KIEs for BH_3, 9-BBN, and AlH_3 indicated that

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[†] Gunma University.

[‡] Rikkyo University.

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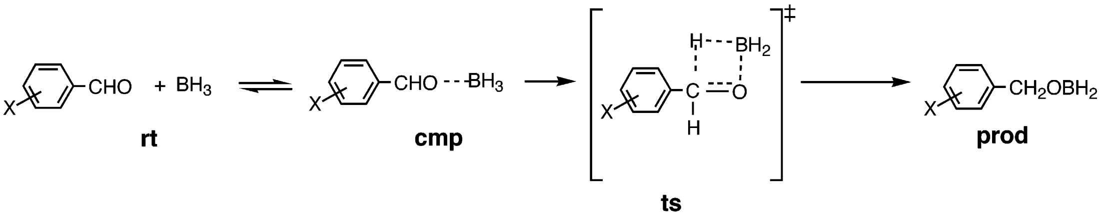
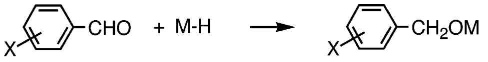
SCHEME 1



the bonding at the carbonyl carbon is changing at the rate-determining TS for these reagents. In contrast, the KIE reported to be unity for DIBAL-H suggested that there was no bonding change at the carbon at the TS, and the mechanism was interpreted to arise from a rate-determining electron-transfer (ET) mechanism. Another experiment showed that the initial complex-formation step between benzaldehyde (BA) and BF_3 in CH_2Cl_2 gave the Hammett ρ value of -3.5, indicating that the complex formation is highly facilitated by electron-donating substituent on the aromatic ring of BA.[3]

In the present study, we examine the intrinsic nature of the reactions of several simple metal hydrides, including BH_3, $BMeH_2$, BMe_2H, AlH_3, and $AlMe_2H$, computationally with BA in the gas phase (eq 1). BMe_2H, and

 (1)

M-H = BH_3, $BMeH_2$, BMe_2H, AlH_3, $AlMe_2H$

$AlMe_2H$ are taken as model reagents of 9-BBN and DIBAL-H. Mechanistic issues to be discussed are (1) reactivity differences between the B and Al reagents, (2) the effect of Me on BH_3 and AlH_3, (3) the nature of the reaction, namely, electrophilic or nucleophilic, (4) TS variation with reactivity, (5) the relation between the TS structure and KIEs, and (6) the effect of dimerization of the boron reagents on the reaction characteristics. The understanding of the effect of solvation on the reaction mechanism is beyond the scope of the present study and will be examined in a future when a computational method that takes into account the solvent effect is reliable and practical.

Computational Method

All calculations were carried out with the Gaussian 98 suite of programs. Geometries were fully optimized with the B3LYP nonlocal hybrid density functional theory[4] using the 6-31G* basis set.[5] All compounds were characterized as minima or saddle points by calculating and diagonalizing the Hessian matrix of energy second derivatives. From statistical mechanics, thermodynamic properties such as entropy, enthalpy, and free energy were calculated from the harmonic vibrational frequencies obtained at the B3LYP/6-31G* level. Isotope effects were calculated from the isotopic shifts of frequencies at B3LYP/6-31G* after scaling with the factor of 0.96 with Bigeleisen's equation.[6] Single-point energy calculations were carried out at the MP2[7] level with the larger 6-311G* basis set[8] to improve energies. Finally, MP2/6-311G* optimization were carried out for the reaction of BA and BH_3, and the results were compared with those at the MP2/6-311G*//B3LYP/6-31G* method. Calculated geometries and energies are listed in Supporting Information.

Results and Discussion

I. Reaction of Monomer Reagents. The reaction profile is basically the same for all reactions. Scheme 1 shows the profile for the reaction of BA and BH_3 as an example. Here BA and BH_3 (reactants, **rt**) form an initial encounter complex (**cmp**), which via a four-membered cyclic TS (**ts**) gives the product (**prod**). The first step is an electrophilic attack of BH_3 on the carbonyl oxygen, and the second is the nucleophilic attack of one of the hydrogens of the metal hydride on the carbonyl carbon.

TS Structures. The structures of the **rt**, the **cmp**, and the **prod** are nearly independent of a substituent on the aldehyde and on the metal hydrides. By contrast, the calculated structures of the **ts** are substituent-dependent, as can be seen in Table 1, where the distances of two reacting bonds (C−H and O−M) are summarized. Both C−H and O−M distances are longer for BAs with a more electron-withdrawing substituent for all reagents. These TS structural variations are nicely related to the reactivity changes in a consistent manner with the Hammond postulate as discussed below. On the other hand, the effect of a change in the reagents on the TS structure is not straightforward. Thus, the change of the central atom from B to Al causes the C−H bond at the **ts** to be shorter for MH_3 but longer for MMe_2H. This is probably because the variation of the reagent is too large a perturbation for the TS structure to be controlled simply by the reactivity.

Reactivities. The enthalpy and free energy values for the reactions are summarized in Table 2. For the reaction of C_6H_5CHO with BH_3, full MP2/6-311G* optimizations were carried out to compare the energies with those from the MP2 single-point calculations on the B3LYP geometries. The results in Table 2 clearly indicate that both methods gave essentially the same reaction energetics. Therefore, we use the MP2 single-point energies in our discussion.

The barrier height for the addition step (**ts/cmp**) does not depend much on the reagents, varying within ca. 2 kcal/mol in free energy for each substituted BA. On the other hand, the energetics of the initial complex-formation step (**cmp/rt**) differs considerably depending on the

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TABLE 1. **C–H and O–Metal Distances for the Reaction of Substituted Benzaldehydes with Metal Hydride**[a]

	cmp	ts		prod	
X	O-metal	C–H	O-metal	C–H	O-metal
		$X-C_6H_4CHO-BH_3$			
p-Me	1.607	1.910	1.629	1.097	1.346
H	1.608	1.933	1.639	1.097	1.346
p-Cl	1.609	1.943	1.645	1.097	1.347
p-NO_2	1.609	2.005	1.679	1.097	1.349
		$X-C_6H_4CHO-BMe_2H$			
p-Me	1.678	1.815	1.674	1.097	1.368
H	1.683	1.884	1.685	1.098	1.368
p-Cl	1.685	1.888	1.691	1.098	1.370
p-NO_2	1.700	1.917	1.735	1.100	1.372
		$X-C_6H_4CHO-AlH_3$			
p-Me	1.988	1.865	1.894	1.100	1.712
H	1.993	1.888	1.902	1.100	1.713
p-Cl	1.997	1.900	1.907	1.100	1.714
p-NO_2	2.011	1.978	1.934	1.102	1.716
		$X-C_6H_4CHO-AlMe_2H$			
p-Me	2.012	1.923	1.925	1.100	1.726
H	2.017	1.948	1.934	1.100	1.727
p-Cl	2.021	1.960	1.940	1.100	1.727
p-NO_2	2.036	2.046	1.973	1.102	1.729

[a] Distances in Å.

TABLE 2. **Relative Enthalpies and Free Energies Based on MP2/6-311G* Energies for the Reaction of Substituted Benzaldehydes with Metal Hydrides**[a]

X	cmp/rt	ts/cmp	ts/rt	prod/rt
		$XC_6H_4CHO-BH_3$		
p-Me	−16.2 (−6.3)	15.5 (17.1)	−0.6 (10.8)	−46.7 (−36.4)
H	−15.7 (−5.4)	15.4 (16.2)	−0.3 (10.8)	−47.0 (−37.0)
H[b]	−15.8 (−5.5)	15.4 (16.0)	−0.4 (10.5)	−46.8 (−37.5)
p-Cl	−15.1 (−4.8)	15.2 (15.9)	0.1 (11.1)	−47.0 (−37.1)
p-NO_2	−13.9 (−3.6)	14.7 (15.4)	0.8 (11.7)	−47.6 (−37.6)
		$XC_6H_4CHO-BMe_2H$		
p-Me	−10.1 (2.8)	13.8 (15.3)	3.8 (18.1)	−46.6 (−34.3)
H	−9.6 (2.7)	13.7 (15.1)	4.1 (17.8)	−46.8 (−35.1)
p-Cl	−9.1 (3.2)	13.4 (14.7)	4.3 (17.9)	−47.0 (−35.3)
p-NO_2	−8.1 (4.1)	12.8 (14.1)	4.7 (18.2)	−47.5 (−36.0)
		$XC_6H_4CHO-AlH_3$		
p-Me	−23.3 (−11.5)	16.9 (16.6)	−6.4 (5.1)	−45.9 (−32.3)
H	−22.8 (−11.0)	16.7 (16.0)	−6.1 (5.0)	−46.2 (−33.3)
p-Cl	−22.1 (−10.3)	16.4 (15.7)	−5.7 (5.4)	−46.5 (−33.5)
p-NO_2	−20.7 (−9.1)	15.6 (14.9)	−5.1 (5.9)	−47.6 (−34.0)
		$XC_6H_4CHO-AlMe_2H$		
p-Me	−19.8 (−7.4)	13.4 (15.2)	−6.4 (7.8)	−43.8 (−32.7)
H	−19.3 (−7.1)	13.1 (14.7)	−6.2 (7.6)	−44.2 (−34.1)
p-Cl	−18.7 (−6.4)	12.7 (14.2)	−5.9 (7.7)	−44.4 (−34.7)
p-NO_2	−17.4 (−5.3)	11.8 (13.2)	−5.6 (7.9)	−45.3 (−34.2)

[a] Relative enthalpies in kcal/mol; **a/b** refers to relative energies of **a** with respect to **b**. Numbers in parentheses are free energies. [b] Energies from MP2/6-311G* optimizations.

reagent. In particular, the complex between BA and BMe_2H is unstable and even less stable than the separated reactants on the free energy basis, whereas for other cases the **cmp** is more stable than the **rt**. The instability of the BA–BMe_2H complex may be due to steric repulsion between the aldehyde and the Me substituent on the metal; the longer O–B bond (1.683 Å) in the BA–BMe_2H complex compared to that (1.608 Å) in the BA–BH_3 complex is consistent with this interpretation (Table 1). Such steric repulsion is small for the Al analogue since the O–Al bond is intrinsically longer.

TABLE 3. **HOMO–LUMO Energies of Substituted Benzaldehydes and Metal Hydrides**[a]

$X-C_6H_4CHO$	HOMO	LUMO	metal hydride	HOMO	LUMO
X = *p*-Me	−6.84	−1.60	BH_3	−9.68	−1.73
X = H	−6.94	−1.71	BMe_2H	−8.25	−0.48
X = *p*-Cl	−7.15	−1.99	AlH_3	−8.36	−1.93
X = *p*-NO_2	−7.57	−3.12	$AlMe_2H$	−7.31	−0.95

[a] In eV/mol at B3LYP/6-31G*.

The overall reactivity (**ts/rt**) is higher for the Al reagents than the B reagents, reflecting that the stabilization by the O–M interaction is larger for Al than for B. The stronger O–Al interaction resulted in a more stable **cmp** for the Al reagents. The electron-donating Me substitution on the central metal makes **cmp** less stable, and the same applies for the **ts** to a smaller extent for both B and Al reactions. Accordingly, the overall reactivity (**ts/rt**) becomes lower, but the reactivity for the addition step itself (**ts/cmp**) becomes slightly higher by the Me substitution on MH_3. The effect of Me is much larger for the B reagents than for Al, likely due to the shorter O–B distance and hence a larger steric repulsion as seen in the complex formation. In summary, the overall reactivity of the four reagents is largely controlled by the stability of the **cmp** and is in the order $AlH_3 > AlMe_2H > BH_3 > BMe_2H$ on the free energy basis.

As for the effect of substituents on BA, the overall reactivity is higher for BA with a more electron-donating substituent, which makes the **cmp** more stable. On the other hand, when the hydride-transfer step is considered as an elementary step (**ts/cmp**), BA is more reactive with an electron-withdrawing substituent on the ring; thus a less advanced C–H bond formation for BA with a more electron-withdrawing substituent is consistent with the Hammond postulate.

Frontier Orbital Energies. As discussed above, an electron-donating substituent on BA facilitates the initial complex formation (**cmp/rt**) as well as the overall reaction (**ts/rt**). On the other hand, substitution of H by Me in MH_3 results in the opposite effects (reduces the reactivity). These effects of the substituents on BA and metal hydrides are consistent with the interpretation in terms of Frontier Orbital analysis. The HOMO–LUMO energies of BAs and the metal hydrides in Table 3 indicate that the principal interaction between the two reactant species is between the HOMO of BAs and the LUMO of the reagents. A benzaldehyde with an electron-donating substituent has a higher HOMO energy and thus should show a higher reactivity. Similarly, the Me substituted metal hydrides has a higher LUMO energy, consistent with a lower reactivity for BMe_2H than BH_3, and for $AlMe_2H$ than AlH_3.

Hammett Plots. On the basis of the calculated enthalpies of the **cmp** and the **ts** relative to the separated reactants (**rt**), the effects of substituents are analyzed in terms of the Hammett equation by converting relative activation and reaction energies to relative rate and equilibrium constants. We use enthalpy rather than free energy in the Hammett treatment because the size of the entropy and hence the free energy depends strongly on low frequencies, which are less reliable than higher frequencies especially for compounds with weak interac-

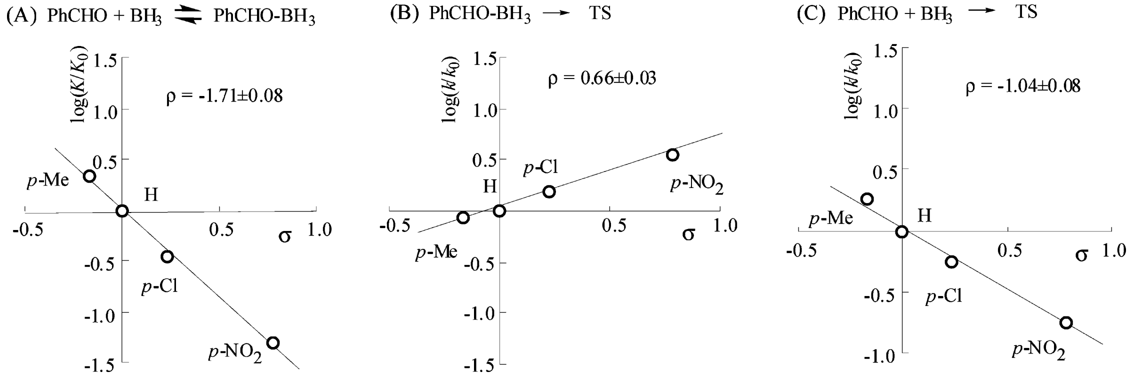

FIGURE 1. Hammett plots for (A) the initial complex-formation equilibrium (**cmp/rt**), (B) the H$^-$-transfer rate from the complex (**ts/cmp**), and (C) the overall rate (**ts/rt**), for the reaction of BA with BH_3.

TABLE 4. Calculated ρ Values for Reactions of Substituted Benzaldehydes with Simple Metal Hydrides[a]

reagent	cmp/rt	ts/cmp	ts/rt	expt ρ value
BH_3	−2.14 (−1.71)	0.71 (0.66)	−1.43 (−1.04)	−0.12
BMe_2H	−2.03 (−1.54)	1.07 (0.83)	−0.97 (−0.71)	−0.76
AlH_3	−2.79 (−2.01)	1.66 (1.08)	−1.13 (−0.92)	1.03
$AlMe_2H$	−2.50 (−1.81)	1.66 (1.20)	−0.83 (−0.61)	0.47

[a] The size of ρ values is based on enthalpy calculated at B3LYP/6-31G*. Numbers in parentheses are ρ values at MP2/6-311G*//B3LYP/6-31G*. Experimental ρ values are for the overall reaction rates of substituted benzophenone with BH_3/THF, 9-BBN/THF, AlH_3/Et_2O, and DIBAL-H/hexane taken from ref 2.

tions such as TSs. It was found that the Hammett plots based on enthalpies gave basically the same ρ values as those based on free energies with much better correlation coefficients.

Plots for the initial complex-formation equilibrium (**cmp/rt**), for the H$^-$-transfer rate (**ts/cmp**), and for the overall rate (**ts/rt**) for BH_3 are illustrated in Figure 1. The ρ values obtained are summarized in Table 4.

Negative ρ values for the initial complex-formation equilibrium (**cmp/rt**) are consistent with the electrophilic nature of the step. Larger (more negative) values for the Al regents compared to those for the B counterparts are in line with higher Lewis acidities (lower LUMO energies) of the Al reagents, which form more stable complexes than the B reagents. The Hammett ρ values for the addition step (**ts/cmp**) are all positive, indicating that the step is nucleophilic in nature, whereas the negative ρ values for the overall rate (**ts/rt**) indicate that the overall rate process is electrophilic.

Comparison with Experimental ρ values. The calculated carbon-14 KIEs for the addition step are small and normal for all the reactions, consistent with the C−H bond formation at the TS. The experimentally observed normal KIEs for BH_3, 9-BBN, and AlH_3 were interpreted to arise from a mechanism in which the nucleophilic addition of hydride to the carbonyl carbon is the rate-determining step.[2] By contrast, the experimental value for DIBAL-H was unity, which suggested that the reaction of the reagent occurred in a different manner from other reagents, presumably via an ET mechanism.[2] Therefore, the experimental ρ value of the DIBAL-H reaction will not be discussed here, even though the reaction in the gas phase should also follow the nucleophilic addition mechanism as for the other reagents.

We now have the calculated Hammett ρ values for the complex-formation equilibrium (**cmp/rt**) and the H$^-$-transfer rate process (**ts/cmp**), together with the experimental ρ values in solution.[2] Although gas phase electronic effects are usually much larger than those in solution,[9] it would be worth comparing the size and, in particular, the sign of the calculated ρ values for the BH_3, BMe_2H, and AlH_3 with the experimental values for BH_3, 9-BBN, and AlH_3 in solution. Under the situations that the rate-determining step is the H$^-$-transfer step and that the initial complexation is in equilibrium, an apparent substituent effect reflects the effect on the energy difference between the H$^-$-transfer TS and an effective ground state. For example, when the **cmp** is more stable than the **rt**, the **cmp** should become the ground state in the kinetics, and thus the substituent effects should reflect only the H$^-$-transfer step (**ts/cmp**). If, on the other hand, the **rt** is more stable than the **cmp**, the substituent effect should be determined for the overall process from the **rt** to the **ts** (**ts/rt**). For BMe_2H, the **cmp** was found to be less stable than the **rt** in terms of free energy in the gas phase. If the same situation holds in solution, which is a reasonable assumption since solvation is likely to be larger for the separated reactants than for the weakly bound complex, the experimentally observed ρ value (−0.76, 9-BBN) similar to the calculated overall rate process (−0.71 for **ts/rt** with BMe_2H) is consistent with the interpretation that the **cmp** plays a negligible role in kinetics in solution. By contrast, the experimentally observed ρ value for AlH_3 was positive (1.03), which indicated that the reaction is nucleophilic in nature. This occurs since AlH_3 is highly electrophilic and forms a stable complex with an aldehyde, which makes the **cmp** the effective ground state in a kinetic sense. The interpretation is supported by the present calculations, which indicate that (1) AlH_3 forms much more stable **cmp** than BH_3 and BMe_2H and (2) the calculated ρ value for the hydride-transfer step (**ts/cmp**) is positive (1.08 (**ts/cmp**), AlH_3). The same applies to the BH_3 reaction but to a less extent; here the **cmp** may contribute partly as the kinetically ground state in solution, and thus the reaction gives the experimental ρ value of only slightly negative (−0.12). Thus, the apparent electrophilic or nucleophilic nature of the reaction arises from the relative stability of the **rt** and the **cmp**.

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TABLE 5. Kinetic and Equilibrium Isotope Effects Calculated at B3LYP/6-31G* for Reaction 1[a]

	cmp/rt		ts/cmp		ts/rt	
substituent	C-EIE	D-EIE	C-KIE	D-KIE	C-KIE	D-KIE
$PhCHO{-}BH_3$						
p-Me	0.996	0.879	1.047	0.975	1.042	0.857
H	0.994	0.878	1.045	0.978	1.038	0.859
p-Cl	0.995	0.881	1.042	0.974	1.037	0.858
p-NO_2	0.996	0.887	1.036	0.983	1.031	0.872
$PhCHO{-}BMe_2H$						
p-Me	0.997	0.889	1.050	0.957	1.047	0.851
H	0.996	0.888	1.049	0.959	1.045	0.852
p-Cl	0.995	0.891	1.050	0.955	1.044	0.851
p-NO_2	0.996	0.899	1.044	0.960	1.040	0.863
$PhCHO{-}AlH_3$						
p-Me	0.997	0.891	1.054	0.948	1.051	0.845
H	0.995	0.890	1.055	0.949	1.050	0.845
p-Cl	0.995	0.893	1.053	0.947	1.049	0.846
p-NO_2	0.996	0.901	1.049	0.960	1.044	0.865
$PhCHO{-}AlMe_2H$						
p-Me	0.998	0.894	1.055	0.956	1.053	0.855
H	0.997	0.893	1.054	0.956	1.051	0.855
p-Cl	0.996	0.904	1.053	0.968	1.049	0.874
p-NO_2	0.996	0.904	1.046	0.968	1.042	0.874

[a] C-EIE (KIE) and D-EIE (KIE) denote the carbonyl-carbon-14 equilibrium (kinetic) isotope effects and α-deuterium equilibrium (kinetic) isotope effects, respectively.

Kinetic Isotope Effects. The calculated isotope effects for the rate and equilibrium steps are listed in Table 5. The calculated carbonyl carbon-14 EIEs for the initial complex formation are nearly unity, whereas the KIEs for other steps are normal. The normal carbon KIEs at the addition step are reasonable since the labeled carbonyl carbon is heavily involved in reaction-coordinate motion at the TS. These carbon KIEs are in good agreement with experimentally observed KIEs for the metal hydride reductions and related addition reactions.[2,10] Secondary α-deuterium KIEs at the aldehyde hydrogen are inverse (smaller than unity) for all cases, consistent with the bond-forming process at the α-carbon center.[11]

The calculated KIEs do not vary dramatically with substituents on BA and on the metal hydrides, reflecting that the reaction mechanism and the TS structures are basically the same. Nevertheless, the KIEs show smooth variations with the change in substituents. Thus, both D and C KIEs are smaller (closer to unity) for BA with a more electron-withdrawing substituent, which is consistent with a more reactant-like TS structure, or a longer C−H distance at the TS with a more electron-withdrawing substituent. Thus, KIEs can be used as a tool to detect of the TS structural variations for a small perturbation such as the substituent on BA. On the other hand, the KIEs do not show noticeable trends with reagents as in the case of the TS structure variations.

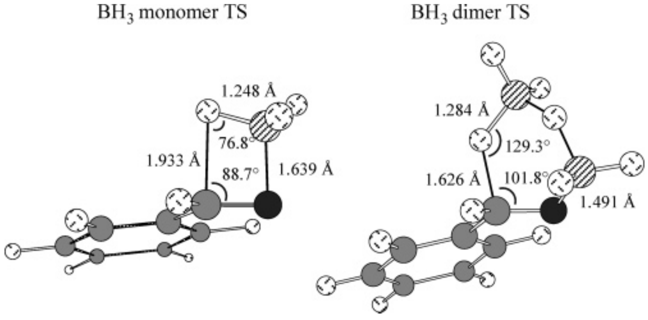

FIGURE 2. TS structures for the reactions of BA with BH_3 and B_2H_6.

TABLE 6. C−H and O−B Distances for the Reaction of Substituted Benzaldehydes with B_2H_6[a]

	cmp	ts		prod	
X	O−B	C−H	O−B	C−H	O−B
p-Me	1.556	1.605	1.487	1.097	1.345
H	1.561	1.626	1.491	1.097	1.346
p-Cl	1.560	1.636	1.494	1.097	1.347
p-NO_2	1.566	1.707	1.507	1.097	1.349

[a] Distances in Å.

II. Reaction of Dimer Reagents. The simple metal hydrides of B and Al are known to form dimers. In the presence of a coordinating species, on the other hand, these reagents, especially BH_3, are known to form stable complexes.[1b−f,12] Thus, BH_3 in THF was reported to exist as a 1:1 complex with THF and to react as a monomer.[1e] However, there is not enough experimental evidence as to whether the reactions of these metal hydrides in general occur as a monomer or a dimer; such information can only be obtained by a kinetic study.[1e,13] To see the effect of aggregation for the reactions in the model reactions in the gas phase, we examined computationally the reactions of dimer reagents and compared the results with those of monomer reagents using the B reagents as examples.

Borane (BH_3) forms a dimer, B_2H_6, which is 36.8 kcal/mol (in enthalpy) and 27.3 kcal/mol (in free energy) more stable than two molecules of BH_3. The reaction scheme for B_2H_6 and BA is similar to that for BH_3 (Scheme 1) except that the reagent is B_2H_6. The TS structure is illustrated in Figure 2 together with that for the BH_3 reaction. Selected geometrical parameters and the reaction energetics are listed in Tables 6 and 7. Comparison of the numbers in Tables 1 and 6 clearly shows that the O−B bond is shorter in the **cmp** and both the O−B and C−H bonds are much shorter at the **ts** for the B_2H_6 reaction than for the BH_3 reaction. The shorter bond distances at the dimer TS is reasonable since the TS assumes six-membered ring structure with less steric restriction, which allows the structure shorter and stronger bonds. The energy profile of the dimer reaction differs considerably from that of the monomer reaction (Tables 2 and 6). B_2H_6 forms an initial complex, which is less stable than the separated reactants as a result of the

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TABLE 7. Relative Enthalpies and Free Energies Based on MP2/6-311G* Energies for the Reaction of Substituted Benzaldehydes with $(BH_3)_2$[a]

X	cmp/rt	ts/cmp	ts/rt
p-Me	7.6 (17.9)	5.6 (7.9)	13.2 (25.8)
H	8.3 (18.7)	5.3 (7.2)	13.6 (25.9)
p-Cl	9.0 (19.3)	5.0 (7.9)	14.0 (27.1)
p-NO_2	10.7 (21.2)	4.2 (6.1)	14.9 (27.3)

[a] Relative enthalpies in kcal/mol; **a/b** refers to relative energies of **a** with respect to **b**. Numbers in parentheses are free energies.

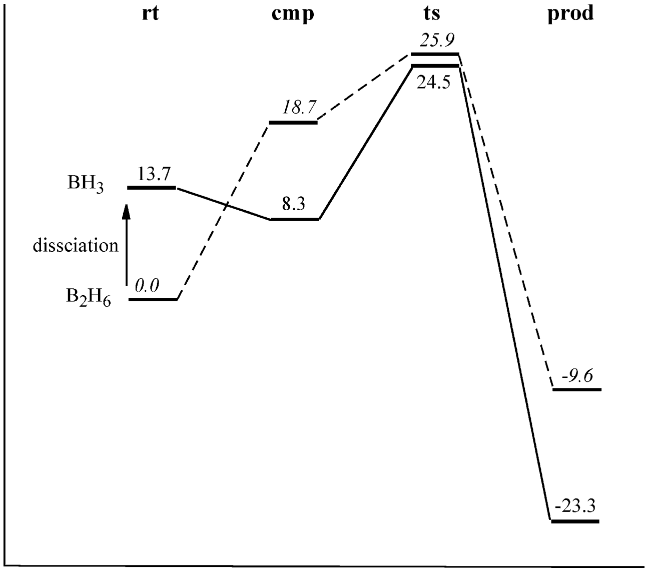

FIGURE 3. Reaction profile for the reaction of BA with BH_3 and B_2H_6. Numbers in roman are relative free energies for the monomer reaction, and those in italic are relative free energies for the dimer reaction.

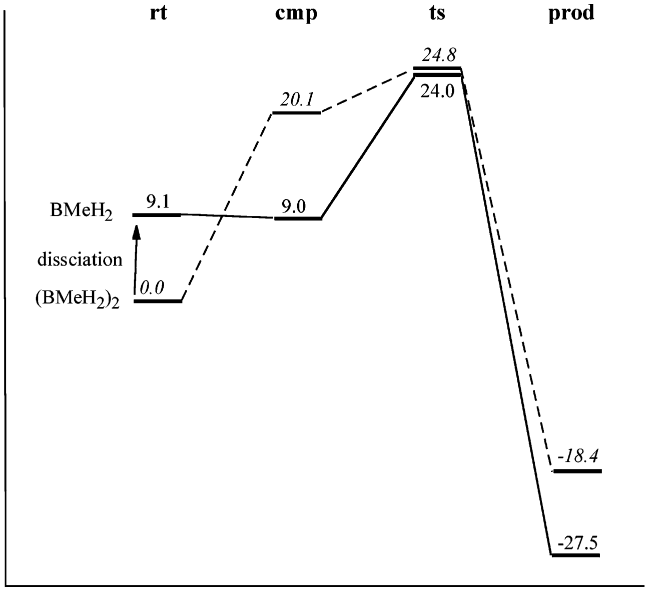

FIGURE 4. Reaction profile for the reaction of BA with $BMeH_2$ and $(BMeH_2)_2$. Numbers in roman are relative free energies for the monomer reaction, and those in italic are relative free energies for the dimer reaction.

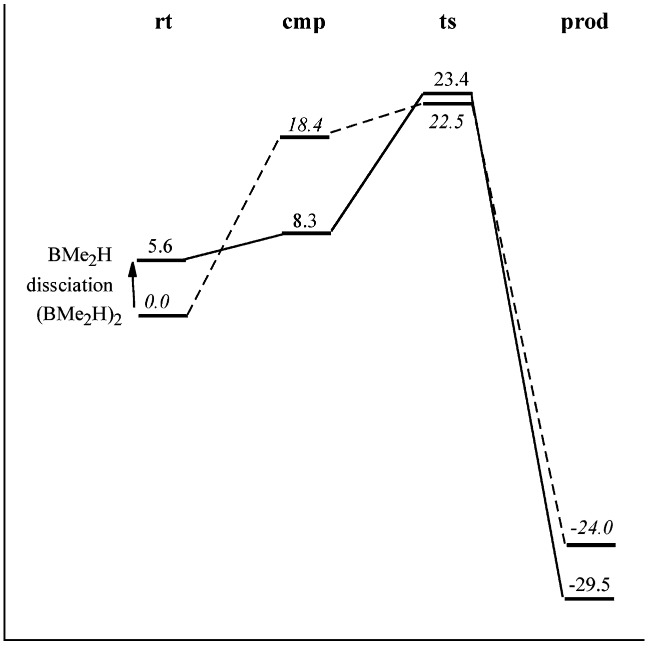

FIGURE 5. Reaction profile for the reaction of BA with BMe_2H and $(BMe_2H)_2$. Numbers in roman are relative free energies for the monomer reaction, and those in italic are relative free energies for the dimer reaction.

marked stability of B_2H_6. The barrier height for the hydride-transfer step (**ts/cmp**) is much lower for the B_2H_6 reaction. The sterically favorable six-membered ring structure with less ring strain clearly makes the hydride transfer feasible. However, because of the relative instability of the complex, the overall barrier (**ts/rt**) is high on both the enthalpy and free energy bases.

When the monomer−dimer equilibrium energy is taken into account with the dimer state taken as reference, the energies along the monomer reaction profile should be raised by a half of the aggregation energy (27.3/2 = 13.7) for one molecule of BH_3. With this correction, the TS free energy for the BH_3 reaction becomes 24.5 kcal/mol with respect to the dimer reactant, which is only slightly smaller than the activation barrier (25.9) for the B_2H_6 reaction (Figure 3). Figure 3 suggests that BH_3 exists mainly as a dimer and that BA reacts with the dissociated monomer reagent.

In Figures 4 and 5 are shown analogous energy diagrams for $BMeH_2$ and BMe_2H. Here again, BA forms the initial complex with the monomer reagents. The addition TS is slightly more stable for the monomer reagent than for the dimer of $BMeH_2$, but the monomer TS is slightly less stable for BMe_2H. Thus, the present calculations show that for all three boron reagents the dimer, which exists as a major component in the gas phase, is expected to dissociate to the monomer and that the monomer forms more a stable complex with BA. The overall reaction proceeds via the monomer TS for BH_3 and $BMeH_2$, whereas the TS with the dimer reagent is slightly more stable for BMe_2H, although the energy differences between the monomer and dimer pathways are small.

The Hammett ρ values for the reactions of substituted BAs with the dimer of the boron reagents are listed in Table 8. Comparison of the Hammett ρ values for the dimer reactions with those for the monomer reactions (Table 4) reveals that the substituent effects are quali-

TABLE 8. Calculated ρ Values for the Reactions of Substituted Benzaldehydes with Dimer Reagents[a]

reagent	cmp/rt	ts/cmp	ts/rt
$(BH_3)_2$	−3.28 (−2.33)	1.67 (1.05)	−1.61 (−1.28)
$(BMeH_2)_2$	−2.08 (−2.00)	1.39 (0.99)	−1.42 (−1.01)
$(BMe_2H)_2$	−2.59 (−1.93)	1.13 (0.85)	−1.46 (−1.09)

[a] The size of ρ values is based on enthalpy calculated at B3LYP/6-31G*. Numbers in parentheses are ρ values at MP2/6-311G*//B3LYP/6-31G*.

tatively the same, with the major difference on the complex-formation step of B_2H_6. The substituent effect on the complex formation (**cmp/rt**) is larger for B_2H_6 than for BH_3. The more negative ρ value for the complex formation with the dimer is likely due to stronger O−B interaction in the dimer complexes, reflected in the O−B distances, 1.561 Å for PhCHO−B_2H_6 and 1.608 Å for PhCHO−BH_3. Such stronger O−B interaction becomes possible because of an additional B−H−BH_3 interaction in the dimer complex. The qualitative similar ρ values for the overall reactions (**ts/rt**) of BH_3 and B_2H_6 are important since these suggest that the mechanistic issue whether the reactions proceed via a monomer or a dimer mechanism would not easily be solved experimentally with the substituent effect on the overall reactivity. Kinetic analyses with different reagent concentrations are required as in the case of RLi.[14]

Conclusions

The present calculations for the reactions of BA with simple metal hydrides in the gas phase lead to the following conclusions. (1) The Al reagents were found to be intrinsically more reactive than the B reagents as expected. The difference is due to a stronger interaction of BA with Al than with B. (2) The Me substitution on BH_3 or AlH_3 makes the reagents less reactive as a result of a weaker interaction between the carbonyl oxygen and the metal of Me-substituted reagents. (3) The Hammett ρ values on **ts/cmp** are in all cases positive, indicting that the hydride-transfer step is nucleophilic in nature. Apparent electrophilic or nucleophilic nature of the reaction arises from the relative stability of the **rt** and the **cmp**. When the **cmp** is much more stable than the **rt,** the **cmp** becomes the effective reactant and then the apparent ρ value for substituted BAs becomes positive. If, on the other hand, the **cmp** is less stable than the **rt**, the **rt** becomes the effective reactant, and therefore the ρ value will be negative. In an intermediate case where the stabilities of the **rt** and the **cmp** are similar, since the ρ value for **cmp/rt** is negative, the overall ρ value can be negative or positive depending on relative contributions of the **cmp/rt** and **ts/cmp** steps to the overall substituent effect. (4) The TS structures vary with the reactivity in a manner consistent with the Hammond postulate for the hydride-transfer step. (5) The TS variations are well reflected in the carbonyl carbon and deuterium KIEs. Thus, KIE is a useful experimental method to detect the variation of a TS structure for related reactions. (6) The comparison of the reaction profiles of the monomer reagents with those of the dimer for the boron reagents showed that even though the dimer is more stable than the monomer in the gas phase, the dimer is expected to dissociate to the monomer, which forms a more stable initial complex with BA. The overall reaction goes through the more stable monomer TS for BH_3, but the dimer reaction becomes increasingly important as the number of the methyl group on B increases, and thus the dimer mechanism becomes favorable for BMe_2H.

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Supporting Information Available: B3LYP/6-31G* optimized Cartesian coordinates and enthalpies for all species reported. This material is available free of charge via the Internet at http://pubs.acs.org.

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