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Hydroboration Reaction and Mechanism of Carboxylic Acids using $NaNH_2(BH_3)_2$, a Hydroboration Reagent with Reducing Capability between $NaBH_4$ and $LiAlH_4$

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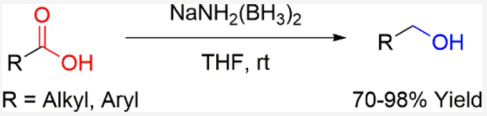
ABSTRACT: Hydroboration reactions of carboxylic acids using sodium aminodiboranate ($NaNH_2[BH_3]_2$, NaADBH) to form primary alcohols were systematically investigated, and the reduction mechanism was elucidated experimentally and computationally. The transfer of hydride ions from B atoms to C atoms, the key step in the mechanism, was theoretically illustrated and supported by experimental results. The intermediates of $NH_2B_2H_5$, $PhCH{=}CHCOOBH_2NH_2BH_3^-$, $PhCH{=}CHCH_2OBO$, and the byproducts of BH_4^-, NH_2BH_2, and $NH_2BH_3^-$ were identified and characterized by ^{11}B and ^1H NMR. The reducing capacity of NaADBH was found between that of $NaBH_4$ and $LiAlH_4$. We have thus found that NaADBH is a promising reducing agent for hydroboration because of its stability and easy handling. These reactions exhibit excellent yields and good selectivity, therefore providing alternative synthetic approaches for the conversion of carboxylic acids to primary alcohols with a wide range of functional group tolerance.

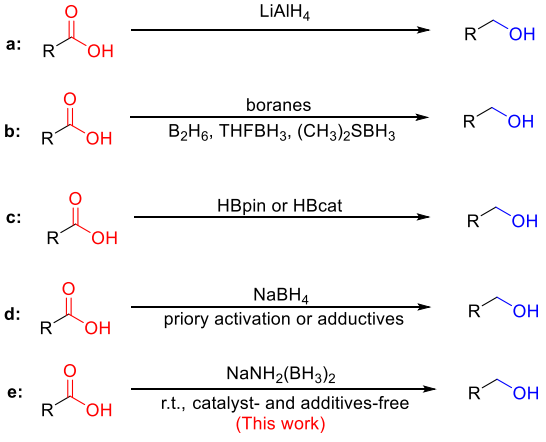


INTRODUCTION

Hydroboration is a type of typical organic reaction in which a boron−hydrogen (B−H) bond adds to C−C, C−O, and C−N double bonds as well as C−C and C−N triple bonds.[1] A well-accepted mechanism of the hydroboration of the C−C multiple bond by three-coordinated boranes (BH_3 group) is that the hydrogen and boron atoms of borane add on the same face of the C−C multiple bond to form a four-membered transition state.[1b,2] This process is concerted in which the formation of the C−B bond proceeds slightly faster than the formation of the C−H bond.[2b] This typical mechanism, however, might be only suitable for explaining the hydroboration by borane reagents such as $THFBH_3$, $(CH_3)_2SBH_3$, and B_2H_6, which will release a BH_3 moiety, a three-coordinated borane with an empty orbital for hydroboration after the dissociation of weak Lewis bases (THF, $(CH_3)_2S$, or BH_3). In these reactions, borane acts as a Lewis acid to initiate reduction by interacting with the reactant at the electron-enriched position using its empty orbital.[2,3] In contrast, when four-coordinated boranes, such as BH_4^- or $L{\cdot}BH_3$ (L is a strong Lewis base) are used as reducing reagents, it is believed that boranes actually act as Lewis bases, and their B−H bonds work as nucleophiles with an electron-deficient center to initiate reduction or hydroboration reactions because there is no available empty orbital in this type of four-coordinated boranes.[4] The hydroboration of C−O or C−N double bonds through four-coordinated boranes has been reported through a variety of ways.[3a,4,5]

The reduction of carboxylic acids to alcohols is an important transformation in synthetic organic chemistry. $LiAlH_4$ is the most widely used reagent for its high reactivity (Scheme 1a).[6] However, poor selectivity limits its application. Hydroboration using B_2H_6, $THFBH_3$, and $(CH_3)_2SBH_3$ borane reagents has also been applied to directly reduce C=O since the middle of the last century (Scheme 1b).[7] Recently, pinacolborane (HBpin) or catecholborane (HBcat) is found efficient for the reduction of C−O, C−N, C−C double bonds, and C−N triple bonds with or without transition metals (Scheme 1c).[8] It is

Scheme 1. Methods for the Reduction of Carboxylic Acids to Primary Alcohols



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known that carboxylic acids could not be directly reduced to alcohols using sodium borohydride ($NaBH_4$), which is another facile reducing reagent with the advantages of chemical stability, low cost, and easy-handling nature. However, carboxylic acids could be reduced using $NaBH_4$ when it is priorly activated to acyl halides, anhydrides, or active esters (Scheme 1d),[9] or in the presence of additives[10] or activators.[11] Unfortunately, these $NaBH_4$-involved methods suffer from additive species, long reaction times, difficulty in work-up and poor selectivity, and the mechanisms are still unclear. Hence, the exploration of the mechanisms of these reactions is of great significance and will facilitate the development of an alternative simple protocol for the chemoselective reduction of carboxylic acids to primary alcohols with better functional group tolerance.

Recently, our group has been focusing on the nucleophilicity of the B−H bonding pair electrons in boranes.[12,13] As a result, the advanced synthetic methods for ammonia borane (NH_3BH_3, AB),[12a] aminodiborane ($NH_2B_2H_5$, ADB),[12b] octahydrotriborate anion ($B_3H_8^-$),[12c,d] and B, N analogs of alkanes ($H(NH_2BH_2)_nH$, n = 1, 2, 3)[12e] have been developed, and the formation mechanisms of these compounds have been elucidated.[12,13] In continuing investigation, various novel borane complexes were applied in conventional reactions to evaluate their behaviors in reduction, examine the nucleophilicity of the B−H bonding pair electrons, and explore their reaction mechanisms as well. After systematic studies, we found that sodium aminodiboranate ($NaNH_2[BH_3]_2$, NaADBH) is readily available, stable, ease-to-handle, and can be used as an efficient reagent for the selective reduction of carboxylic acids to primary alcohols (Scheme 1e).

Aminodiboranate anions ($NH_2(BH_3)_2^-$, $ADBH^-$) were proposed as an ammonium salt ($[NH_4][NH_2(BH_3)_2]$) in 1936, considering them as a possible structural formula of the diammoniate of diborane (DADB).[14] Its sodium salt ($NaNH_2(BH_3)_2$, NaADBH) was observed in 1938. Until 2010, it was first synthesized through the reaction of $NaNH_2$ or metal Na with AB;[15] then, its synthetic methods have been improved, and its reactivity has been preliminarily explored.[12e,13c] In this work, we investigated the hydroboration reactions of carboxylic acids to the corresponding primary alcohols at room temperature using NaADBH as the hydroborating reagent without other additives (eq 1). The reaction mechanism was studied experimentally and computationally.

$$RCOOH + NaNH_2(BH_3)_2 + 3\,H_2O \rightarrow RCH_2OH + NH_3BH_3 + Na[B(OH)_4] + H_2 \quad (1)$$

RESULTS AND DISCUSSION

Determination of Reaction Conditions. NaADBH is a crystalline solid, and it is stable in THF solution for several days at room temperature (Figure S1). To investigate the activity of NaADBH, cinnamic acid **1a** was selected as a typical representative of carboxylic acids to establish broadly applicable hydroboration conditions (Table 1). First, different solvents were examined, and the results indicated that the reaction proceeded very smoothly in tetrahydrofuran (THF), acetonitrile (CH_3CN), dioxane, diethyl ether (Et_2O), 1,2-dimethoxyethane (DME), and dimethyl sulfoxide (DMSO) (Table 1, entries 1−6). The best result was obtained with THF. When methanol (MeOH), *N*,*N*-dimethylformamide (DMF), and water were used, no product was obtained because of the decomposition of NaADBH in these solvents (Table 1, entries 7−9).

Table 1. Reduction of Cinnamic Acid in Different Solvents at Room Temperature[a]

entry	solvent	t/h	yield (%)[b]
1	**THF**	**2.5**	**90**
2	CH_3CN	2.5	86
3	dioxane	2.5	88
4	Et_2O	6	80
5	DME	2.5	85
6	DMSO	2.5	85
7	MeOH	2.5	n.r.
8	DMF	2.5	n.r.
9	H_2O	2.5	n.r.

[a]conditions: **1a** (2.0 mmol), $NaNH_2(BH_3)_2$ (3.6 mmol) in different solvents (15 mL) at room temperature. [b]Isolated yield.

Then, we examined how many hydrides would take part in these reactions because NaADBH contains six negatively charged hydrogens (B−H). Based on the reduction of cinnamic acid to cinnamyl alcohol, 3 equiv hydrides are stoichiometrically required: one for neutralizing the proton of the acid to form H_2 and two for the reduction of carbonyl to form a methylene group. However, experimental results show that this transformation needs at least 1.5 equiv NaADBH (Table 2), indicating that reduction is more complicated than expected. In fact, a 1:1.8 ratio of cinnamic acid to NaADBH was used in the reactions.

Table 2. Reduction of $NaNH_2(BH_3)_2$ with Cinnamic Acid at Different Molar Ratios in THF at Room Temperature[a]

entry	**1a**: $NaNH_2(BH_3)_2$	t/h	yield (%)[b]
1	1:4	0.5	88
2	1:3	1	90
3	1:1.8	2.5	90
4	1:1.5	24	86
5	1:1	24	39[c]

[a]conditions: **1a** (2.0 mmol), $NaNH_2(BH_3)_2$ (x mmol) in THF at room temperature. [b]isolated yield. [c]Determined by ^1H NMR (Figure S30).

An Examination of the Scope of Hydroborations. After the determination of solvents and molar ratio, we investigated the reactions in a wide range of aromatic and aliphatic carboxylic acids with different functional groups (Table 3). The reactions for all the carboxylic acids underwent smoothly and afforded the corresponding primary alcohols in good to excellent yields. The reaction of benzoic acid and 4-halo benzoic acids with NaADBH gave primary alcohols with good to excellent selectivity, confirming that weak electron-withdrawing groups have no impact on this transformation (**2b**−**2f**). Electron-donating or highly electron-withdrawing benzoic acids also gave the corresponding products in very good to excellent yields (**2g**−**2s**). When 4-formayl benzoic acid was used, 1,4-benzenedimethanol **2t** was obtained in 90% yield.

The reduction of 1-naphthyl carboxylic acid with NaADBH provided 1-naphthyl methanol (**2u**) in 87% yield. Finally, we extended the substrate to dicarboxylic acids and aliphatic acids in order to explore the potential applications of this protocol,

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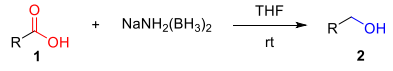
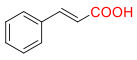
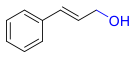
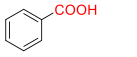
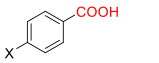
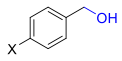
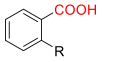
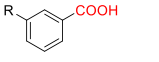
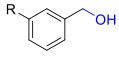
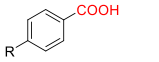
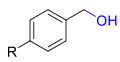
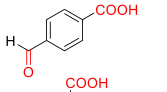
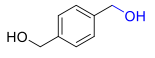
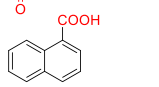
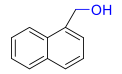
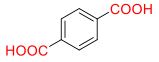
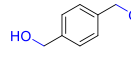
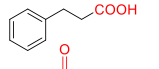
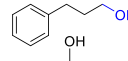
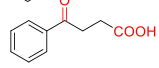
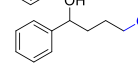
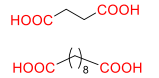
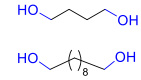
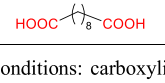
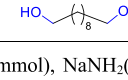
Table 3. Reduction of Carboxylic Acids to Primary Alcohols with $NaNH_2(BH_3)_2$[a]



carboxylic acid	reaction time	alcohol	yield (%)[b]
	2.5		**2a**, 90%
	1		**2b**, 72%
	6 6 8 8		X=F, **2c**, 72% X=Cl, **2d**, 92% X=Br, **2e**, 90% X=I, **2f**, 90%
	1.5 8 15 8		R=Me, **2g**, 90% R=OMe, **2h**, 75% R=OH, **2i**, 70% R=NO_2, **2j**, 92%
	1.5 8 8		R=Me, **2k**, 87% R=OMe, **2l**, 78% R=NO_2, **2m**, 70%
	2 4.5 8 16 6 8		R=Me, **2n**, 90% R=^{t}Bu, **2o**, 80% R=OMe, **2p**, 78% R=OH, **2q**, 70% R=CN, **2r**, 90% R=NO_2, **2s**, 90%
	18		**2t**, 90%
	6		**2u**, 87%
	24		**2v**, 90%[c]
	2		**2w**, 90%
	12		**2x**, 72%
	4		**2y**, 80%[c]
	10		**2z**, 98%[c]

[a] conditions: carboxylic acid **1** (2.0 mmol), $NaNH_2(BH_3)_2$ (3.6 mmol) in THF (15 mL) at room temperature. [b] isolated yield. [c] 7.2 mmol NaADBH was used.

and the hydroboration of these carboxylic acids were also successful under the same conditions (**2v**–**2z**). NaADBH is a stable solid at room temperature, which makes it easy to handle. NaADBH reduces the carbonyl group of carboxylic acids, as well as aldehydes (**2t**) and ketones (**2x**), and does not react with the X^-, OH^-, CN^-, OMe^-, and NO_2^- groups. It is noteworthy that the carboxyl group is reduced selectively to produce the expected allylic alcohol as the sole product (**2a**), showing an outstanding chemoselectivity.[1b,2c,3b,10a]

Mechanism of Hydroboration. In order to study the reaction mechanism, the reaction was monitored by ^{11}B NMR (Figure 1). As the reaction proceeded, the NaADBH signal (δ = −19.90 ppm) decreased, and two sets of peaks appeared and increased, which are assigned to sodium amidoborane ($NaNH_2BH_3$, NaAB, δ = −21.68 ppm) and $NaBH_4$ (δ = −43.37 ppm),[12e] respectively. One additional small signal at δ = 19.27 ppm was assigned to trialkylboraxine compared to the literature,[7c,16] which was weak because of its poor solubility. Unfortunately, a set of signals observed at δ = 2.6–3.8 ppm cannot be assigned with certainty, but they are very likely due to the boron species involving B–O bond. In about 2 h,

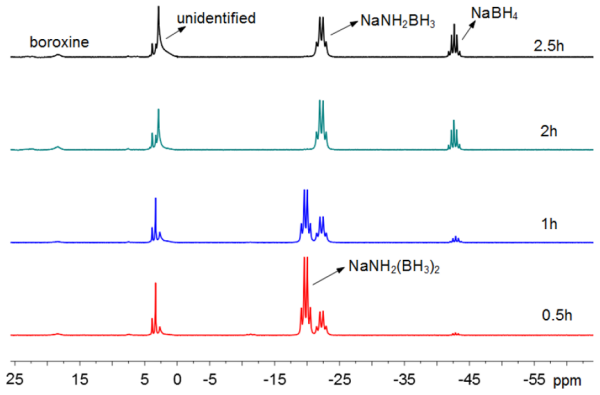


Figure 1. ^{11}B NMR spectra for the reaction of $NaNH_2(BH_3)_2$ (1.8 equiv) and cinnamic acid (1 equiv) in THF-d_8 at different time points.

NaADBH was consumed completely, and the hydroboration reaction was ceased. ^{11}B NMR investigation demonstrates that the reaction mechanism is complicated, and part of NaADBH was converted into NH_2BH_2 and $NaBH_4$.

In order to further delineate the mechanisms, M06-2X[17] calculations were performed using the Gaussian 09 program.[18]

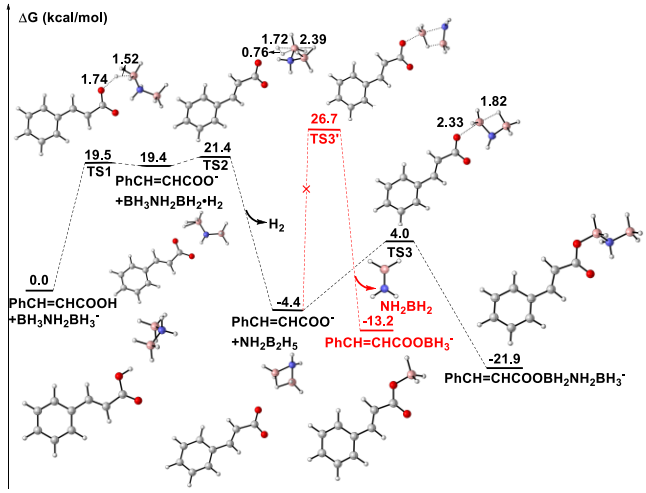


Figure 2. Formation of $PhCH{=}CHCOOBH_2NH_2BH_3^-$ (distance in Å).

As shown in Figures 2-4, there are three stages for the reduction of cinnamic acid (PhCH=CHCOOH) using NaADBH. It should be mentioned that the cation Na^+ can be dissociated with the amidoborane anion and coordinated to the THF molecule to form stable THF·Na^+ in this kind of system,[12e] so we constructed the anion $ADBH^-$ as the real substrate in the molecular models and simulations. In the first stage, PhCH=CHCOOH reacts with $ADBH^-$, generating H_2, ADB ($NH_2B_2H_5$), and sodium salt of cinnamic acid ($PhCH{=}CHCOO^-$) via transition states TS1 (19.5 kcal/mol) and TS2 (2.0 kcal/mol). In this stage, the proton of PhCH=CHCOOH interacts with the negatively charged hydrogen of the BH_3 group in $ADBH^-$ to initiate the formation of molecular hydrogen complexes and then leads to hydrogen elimination to form ADB. This hydrogen elimination process is consistent with H_2 release through the dihydrogen bond.[13] Subsequently, the resulting $PhCH{=}CHCOO^-$ anion reacts

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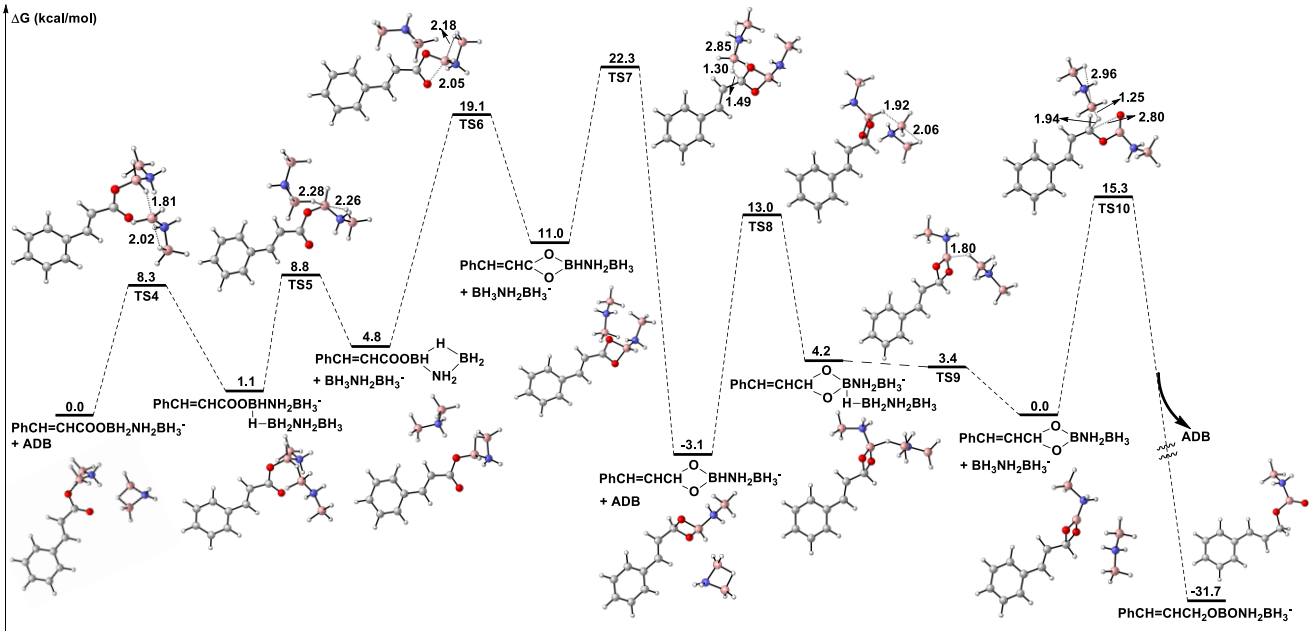

Figure 3. Formation of $PhCH{=}CHCH_2OBONH_2BH_3^-$ (distance in Å).

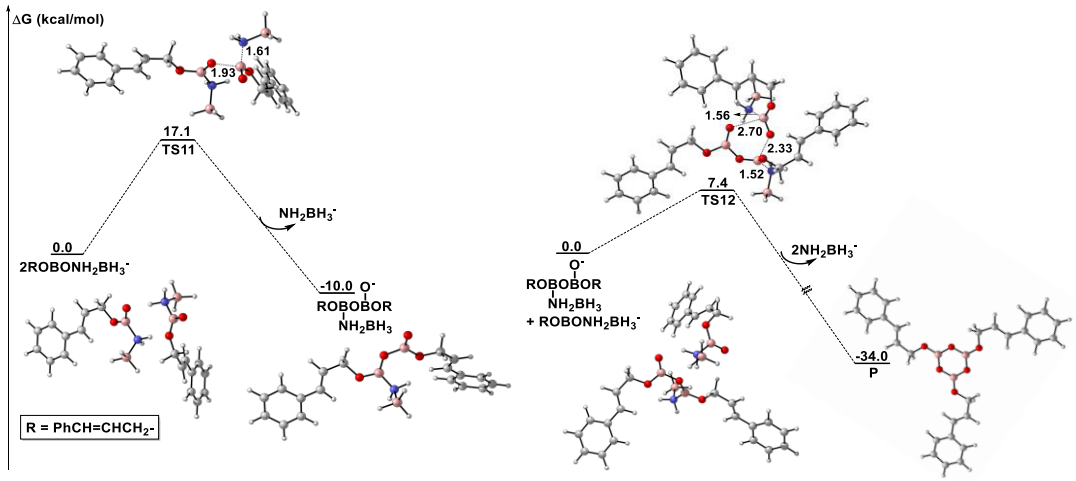

Figure 4. Formation of $(PhCH{=}CHCH_2OBO)_3$ (distance in Å).

with ADB to afford $PhCH{=}CHCOOBH_2NH_2BH_3^-$ anion through TS3 (8.4 kcal/mol). The other possible pathway through TS3' with an energy barrier of 31.1 kcal/mol can be ruled out (red part in Figure 2).

The second stage is presumed to be an ADB-catalyzed reduction process based on the theoretical results. First, ADB abstracts a H^- from the BH_2 moiety in the $PhCH{=}CHCOOBH_2NH_2BH_3^-$ anion via TS4 (8.3 kcal/mol) and TS5 (7.7 kcal/mol) to form $ADBH^-$ and $PhCH{=}CHCOOBH(\mu\text{-}NH_2)(\mu\text{-}H)BH_2$, which can be considered as a derivative of ADB in which one terminal hydride ion (H^-) is substituted by a $PhCH{=}CHCOO^-$ anion. Then, the resulting intermediate is further transformed to a C−O−B−O four-membered ring $PhCH{=}CHC(\mu\text{-}O)(\mu\text{-}O)BHNH_2BH_3$ intermediate via TS6 (14.3 kcal/mol). In the following step, the B−H bond of $ADBH^-$ interacts with the C atom of a C−O−B−O four-membered ring in $PhCH{=}CHC(\mu\text{-}O)(\mu\text{-}O)BHNH_2BH_3$ to form ADB and $PhCH{=}CHCH(\mu\text{-}O)(\mu\text{-}O)BHNH_2BH_3^-$ via TS7 (11.3 kcal/mol). Afterward, ADB repeatedly abstracts the H^- anion from the BH moiety of $PhCH{=}CHCH(\mu\text{-}O)(\mu\text{-}O)BHNH_2BH_3$ to form $ADBH^-$ and $PhCH{=}CHCH(\mu\text{-}O)(\mu\text{-}O)BNH_2BH_3$ via TS8 (16.1 kcal/mol) and TS9, and then, a H^- from the $ADBH^-$ anion attacks the C atom in the C-O-B-O four-membered ring of $PhCH{=}CHCH(\mu\text{-}O)(\mu\text{-}O)BNH_2BH_3$, leading to the opening of the C−O−B−O four-membered ring via TS10 (15.3 kcal/mol) to form a $PhCH{=}CHCH_2OBONH_2BH_3^-$ anion after the release of ADB. It should be noted that the energy barrier via TS9 is 1.1 kcal/mol without the zero-point and thermal-free energy correction, but the energy difference between $PhCH{=}CHCH(\mu\text{-}O)(\mu\text{-}O)B(NH_2BH_3)(\mu\text{-}H)BH_2NH_2BH_3$ and TS9 becomes negative (−0.8 kcal/mol) with the zero-point and thermal-free energy correction, indicating the reaction step is a barrier-less process.

In the third stage, two molecules of $PhCH{=}CHCH_2OB(O)\text{-}NH_2BH_3^-$ combination happen, and one molecule of $NH_2BH_3^-$ dissociates via TS11 (17.1 kcal/mol) to generate $PhCH{=}CH\text{-}CH_2OB(NH_2BH_3)OB(O)OCH_2CH{=}CHPh$, which then reacts with another molecule of $PhCH{=}CHCH_2OB(O)\text{-}NH_2BH_3^-$ via TS12 (9.3 kcal/mol) to form a six-membered ring product in which the B and O atoms are

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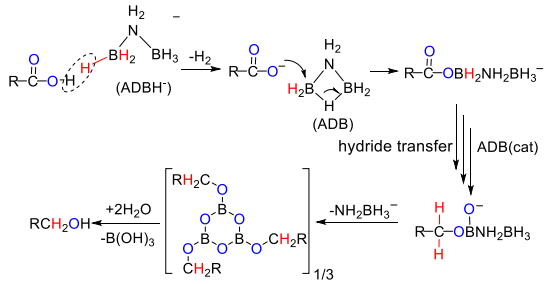
located alternatively. From the six-membered ring product, the final PhCH=CHCH$_2$OH alcohol product was obtained after hydrolysis.

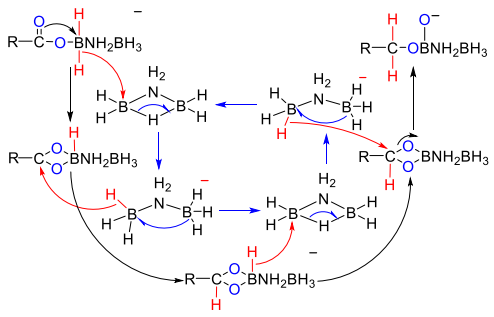
Based on these experimental and theoretical studies, the plausible mechanism has been summarized and depicted in Scheme 2.

Scheme 2. Proposed Mechanism



Hydride Ion-Transfer Reactions. In the second stage, the key step is the transfer of hydride ions (H^-) from the BH_2 moiety to the C atom of the carbonyl group, forming a methylene group. The H^- transfer from borane to the C atom was first proposed in a reaction of diborane with organic compounds incorporating the carbonyl group in 1939,[1a] and this transfer has been mentioned in the literature over the past 80 years.[3,5e] The details, however, have never been reported thus far.[5g] In the reaction of diborane with carboxylic acids, although the neutralization of the proton and the hydride ions was extensively studied, the transfer of hydride ions has not been fully discussed.[3b] Based on the theoretical and experimental results in this work, we notice that H^- relocation is benefited from the interconversion between the $ADBH^-$ anion and the ADB molecule, as shown in Scheme 3. Thus, it is considered that ADB plays a catalytic role in this reduction reaction.

Scheme 3. ADB catalyzes the hydride ion transfer from the B atom to the C atom



According to the proposed mechanism, 1 equiv of cinnamic acid would consume 1 equiv of NaADBH in the reaction to produce 1 equiv of H_2, NaAB, and cinnamyl alcohol after hydrolysis. In this process, ADB was formed, and it played a catalytic role. However, ADB was not observed using ^{11}B NMR to monitor the reaction process (Figure 1). The reactant ratio predicted in the proposed mechanism is inconsistent with the experimental results. Furthermore, the BH_4^- anion was observed in ^{11}B NMR (Figure 1), and the NH_2BH_2 species were captured in the reaction process (Figure S2), but they are not engaged in the proposed mechanism. Multiple discrepancies between the proposed mechanism and experimental observation imply that the reaction was not simply proceeded as described in the previously proposed mechanism, and some reactions proceeded behind the scenes, which inspired us to investigate this reaction in more detail.

Characterization of the Formed ADB. The formation of ADB is the key step in the proposed mechanism. Without the formation of ADB, the reaction process may cease at the stage of sodium cinnamate because, in general, sodium cinnamate cannot be reduced.[10a] It is the *in situ* formed ADB that continually reacts with the PhCH=CHCOO$^-$ anion to form the anionic PhCH=CHCOOBH$_2$NH$_2$BH$_3^-$ intermediate and then catalyzes the transformation from PhCH=CHCOOBH$_2$-NH$_2$BH$_3^-$ to PhCH=CHCH$_2$OB(O)NH$_2$BH$_3^-$. In order to prove the participation of ADB in the reaction process, the reaction was carried out at low temperatures to capture the *in situ*-formed ADB intermediate. At −40 °C, ADB and PhCH=CHCOO-BH$_2$NH$_2$BH$_3^-$ intermediates were monitored by ^{11}B NMR, and the broad signal at δ = −27.15 ppm was assigned to the B atom in ADB (Figure S3).[12b] In addition, the broad triplet signal at δ = −4.04 ppm was assigned to the B atom in the BH_2 moiety, and the quartet signal at δ = −21.71 ppm was assigned to the B atom in the BH_3 moiety in PhCH=CHCOOBH$_2$NH$_2$BH$_3^-$. Attempts to isolate this intermediate were carried out but in vain. Meanwhile, the hydrogen evaluated from the reaction was confirmed by ^{1}H NMR (Figure S4).

ADB Catalytic Decomposition of NaADBH. The observation of BH_4^- in the ^{11}B NMR spectra (Figure 1) and the capture of NH_2BH_2 by cyclohexene (Figure S2) are contradictious to the proposed mechanism in which only NaAB and a PhCH=CHCH$_2$OBO trimer are the final products before hydrolysis. We found that although pure NaADBH in THF solution is stable (Figure S1), ADB can expedite the NaADBH decomposition. When 1 mL of 0.4 M ADB in the THF solution was added to 10 mL of 0.4 M NaADBH in THF, the BH_4^- anion signal can be observed in comparison with the control experiment (Figure S5). The signal of Cy$_2$BNH$_2$ was also captured by ^{11}B NMR after the addition of cyclohexene to the reaction mixture (Figure S6).[13c] It is, thus, concluded that the formation of ADB in the first stage induces the catalytic decomposition of NaADBH to $NaBH_4$ and NH_2BH_2.

The process of the ADB-catalyzed decomposition of NaADBH was also simulated (Figures S7 and S8). In the first step, ADB in THF decomposed to $THFBH_3$ and NH_2BH_2 *via* TS01 (22.6 kcal/mol), and then, the resulting $THFBH_3$ interacts with the $ADBH^-$ anion to afford the BH_4^- anion and ADB *via* TS02 (20.1 kcal/mol) and TS03 (10.3 kcal/mol). According to the theoretical simulation, $THFBH_3$ can react with NaADBH to produce ADB and the BH_4^- anion. Thus, the reaction of $THFBH_3$ with NaADBH was carried out. As a result, the formation of ABD and the BH_4^- anion was observed, but no NH_2BH_2 species could be detected (Figure S8). Thus, it is clear that the ADB formed in the process not only catalyzes the hydroboration of acids but also catalyzes the decomposition of NaADBH. This finding also explained why at least the 1:1.5 of cinnamic acid to NaADBH ratio was required in the processes, that is, 1 equiv of NaADBH participated in the reaction (one hydride with the proton of acid and two more for reduction, and other BH_3 group go to NaAB) and approximately 0.5 equiv of NaADBH decomposed to NH_2BH_2 and the BH_4^- anion was catalyzed by ADB.

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The formation of NaAB in the proposed mechanism is not only proved by ^{11}B NMR but also confirmed in the reaction of *p*-hydroxyl benzoic acid with NaADBH, in which ammonia borane (AB) was observed as the product (Figure S9). It is believed that AB is formed through the reaction in which *in situ*-formed NaAB abstracts hydrogen from the hydroxyl group in *p*-hydroxyl benzoic acid.[19] After hydrolysis, *p*-hydroxyl-benzyl alcohol was produced (**2j**). A similar phenomenon was observed in the reduction of *o*-hydroxyl benzoic acid, in which *o*-hydroxyl-benzyl alcohol was formed (**2n**). Furthermore, more time was required for the reaction of the hydroxyl-substituted reactant than others (**2j**, **2m**, and **2n** in Table 3), and this could be related to the low solubility of the corresponding sodium salt.

Characterization of the Formed Boroxine. In the proposed mechanism, the alternatively located B,O six-membered ring, the $\{PhCH{=}CHCH_2OBO\}_3$ trimer, is the final product of the reduction. After hydrolysis, cinnamyl alcohol was obtained. B,O six-membered ring was reported in the literature, but its characterization was not complete.[16] The $\{PhCH{=}CHCH_2OBO\}_3$ trimer is considered to be chemically stable based on the theoretical calculations (Figure 4). However, its characterization on mass spectroscopy (MS) (both gas chromatography−mass spectroscopy (GC−MS) and high-resolution mass spectroscopy−electrospray ionization (HRMS-ESI)) failed.

The reduction products were further characterized by NMR. After the reaction of cinnamic acid with NaADBH, the reducing product existed in both the precipitate and solution. In order to isolate the six-membered ring product, the reaction mixture was filtrated, and the solvent was removed. The residual was extracted using toluene and then removed to afford the product (Figures S10−S14). In ^{11}B NMR, the broad band of signals that appeared at δ = 19.24 ppm was assigned to the six-membered ring product, and a quartet at δ = −21.95 ppm can be assigned to NaAB. The small peak that appeared at δ = 2.66 ppm cannot be assigned (Figures S10 and S11). After the addition of D_2O, the six-membered ring product is converted to cinnamyl alcohol, and at the same time, NaAB is converted to AB (Figures S15−S19). In ^{1}H NMR, the hydrogens in the aromatic ring appeared at δ = 7.42−7.22 ppm, and two hydrogens in the CH=CH moiety appeared at δ = 6.65−6.35 ppm before hydrolysis, and the two hydrogens of the methylene group appeared at δ = 4.58−4.47 ppm. It is worth noting that all the three types of hydrogen appeared as a set of signals except the single signal (Figures S12 and S13). This implied that the six-membered ring product isolated here was not a pure product and could be a mixture containing species that might be related to mono-, di-, or triacyloxyboranes in coupling consideration with the unassigned signals at δ = 2.6−3.8 ppm in ^{11}B NMR spectra.[16a,20] However, the identification of the methylene group by NMR spectroscopy confirmed that the reduction reaction was complete. Finally, all the species in the mixture can be converted into cinnamyl alcohol after hydrolysis based on ^{1}H NMR (Figures S17 and 18). A similar observation was obtained for the reaction of benzoic acid with NaADBH (Figures S20−S29). These experimental results, characterizing the reducing products by MS and ^{11}B, ^{1}H, and ^{13}C{^{1}H} NMR, are consistent with the proposed mechanism.

Reduction of Carboxylic Acid Derivatives and Nitriles with NaADBH. The reaction of NaADBH with nitrile and carboxylic acid derivatives such as acyl chloride, amide, and ester compounds were investigated. It was found that NaADBH reacted with benzoyl chloride at room temperature. It does not react with methyl phenylpropionate and phenyl-nitrile at room temperature, but the corresponding alcohols and amines can be obtained at reflux in THF, while NaADBH did not react with benzoamide whether at room temperature or reflux.

Comparison of the Reducing Capability of NaADBH with That of Typical Hydroboration Reagents. Although $THFBH_3$, $(CH_3)_2SBH_3$, and B_2H_6 are commonly used hydroboration reagents, their applications are somehow limited because of their sensitivity to air and moisture. In contrast, $NaBH_4$ and lithium aluminum hydride ($LiAlH_4$), as solid reducing reagents, are often used in organic chemistry.[4,6] $NaBH_4$ is specifically used for the reduction of aldehydes and ketones to alcohols for its mild reducing capacity,[4] and $LiAlH_4$ is an extremely powerful reducing reagent for almost all the reducible groups.[6] As discussed above, the reducing capacity of NaADBH is somewhere between these two extremes which will be an advantage for the selective requirement. Here, we made a comparison of the reducing capability of $NaBH_4$, $LiBH_4$, NaADBH, $THFBH_3$, and $LiAlH_4$ (Table 4) based on the present work and the literature,[21] which revealed that NaADBH can reduce aldehydes, ketones, acyl chloride, and carboxylic acids to alcohols but not for ester, amide, nitrile, nitro, and C-C double bond at room temperature. Ester and nitrile can also be reduced under reflux. While $NaBH_4$ only reduced aldehydes, ketones, and acyl chloride, $LiAlH_4$ reduced almost all the reducible groups except the C−C double bond (Table 4). Considering its availability and the high stability both in the solid state and in solution, NaADBH is undoubtedly an excellent reducing reagent to meet the requirements for selective reduction where either $NaBH_4$ or $LiAlH_4$ often fails to do so.

Table 4. Comparison of the Reducing Capability of Selective Reducing Agents[21a]

	$NaBH_4$[4b]	$LiBH_4$[21b]	NaADBH	$THF{\cdot}BH_3$[7c]	$LiAlH_4$[21c]
RCHO	×	×	×	×	×
R_2CO	×	×	×	×	×
RCOCl	×	×	×	O	×
RCO_2R'	O	×	⊗	⊗	×
RCO_2H	O	O	×	×	×
$RCONR'_2$	O	O	O	×	×
RCN	O	O	⊗	×	×
RNO_2	O	O	O	O	×
$RCH{=}CH_2$	O	O	O	×	O

[a]× the hydroboration reaction was taken place at room temperature; ⊗ the hydroboration reaction was taken place under reflux; O the hydroboration reaction cannot take place.

These advantages of NaADBH as a reducing reagent for hydroboration make it possible to develop an alternative simple protocol for the chemoselective reduction of carboxylic acids to primary alcohols. In addition, this work provides insights into the study of the general mechanism of the hydroboration of the C−O and C−N double bonds using borane complexes.

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CONCLUSIONS

The transformation of various carboxylic acids to primary alcohols by hydroboration using NaADBH was systematically investigated, and the reduction mechanism was proposed based on the experimental results and computer modeling. In our proposed mechanism, the hydride ion-transferring process from the B atom to the C atom was convincingly illustrated, that is, the forming ADB abstracts a hydride ion from the BH_2 group in the $PhCH{=}CHCOOBH_2NH_2BH_3^-$ intermediate to form the $ADBH^-$ anion; then, the B-H bonding pair electrons of the BH_3 group in $ADBH^-$ nucleophilically interact with the electron-deficient C atom to initiate the reduction reactions. Consequently, $ADBH^-$ is converted to ADB by transferring a hydride ion to the C atom. Reduction was ceased by the transferring of the second hydride ion, and the carbonyl was reduced to methylene, leading to the formation of $PhCH{=}CHCH_2OBO$ intermediates. The ADB, $PhCH{=}CHCOOBH_2NH_2BH_3^-$, $PhCH{=}CHCH_2OBO$ intermediates, and the BH_4^-, NH_2BH_2, $NH_2BH_3^-$ byproducts were identified and characterized by ^{11}B and ^{1}H NMR. NaADBH is a good reducing reagent for hydroboration because of its stability and easy-to-handle nature, showing very good to excellent yields and selectivity, making it possible to be developed as an alternative simple protocol for the chemoselective reduction of carboxylic acids to primary alcohols. The reducing capacity of NaADBH lies between $NaBH_4$ and $LiAlH_4$ with tolerance on functional groups. In addition, this work provides insights into the study of the general mechanism of the hydroboration of the C−O and C−N double bonds using borane complexes.

EXPERIMENTAL SECTION

General. The ^{11}B NMR spectra were recorded using a 128 or 193 MHz spectrometer and externally referenced to $BF_3{\cdot}OEt_2$ in C_6D_6 (δ = 0.00 ppm). The ^{1}H NMR spectra were recorded using a 400 MHz or 600 MHz spectrometer. The $^{13}C\{^{1}H\}$ NMR spectra were recorded at 100 or 151 MHz. The ^{19}F NMR spectra were recorded at 576 MHz. Chemical shifts were expressed in parts per million (δ) downfield from the internal standard tetramethylsilane and were reported as s (singlet), d (doublet), t (triplet), dd (doublet of doublet), and m (multiplet). The coupling constants J were given in hertz (Hz). High-resolution mass spectra were obtained via the ESI mode using a MicrOTOF mass spectrometer. X-ray diffraction (XRD) data were collected with a Rigaku D/max 2500 diffractometer using the Cu/Ka radiation (λ = 0.1542 nm, 40 kV, 100 mA). The conversion of starting materials was monitored by thin-layer chromatography (TLC) using silica gel plates (silica gel 60 F254 0.25 mm), and the components were visualized by observation under UV light (254 and 365 nm).

Computational Details. The M06-2X[17] calculations were performed using the Gaussian 09 program.[18] The basis set 6−311++G(d, p) was employed for all the atoms involved in the model reaction. The solvent effect was considered using the SMD model[22] in the THF solvent for all kinds of calculations. After the structural optimizations for all the stationary points, frequency calculations at the same level of theory were carried out to identify all the stationary points as minima (zero imaginary frequency) or transition states (only one frequency) and to provide corrections for free energies. The Cartesian coordinates and the vibrational frequencies of the studied model species are listed in the Supporting Information.

Synthesis of Sodium Aminodiboranate $NaNH_2(BH_3)_2$, (NaADBH) using the Modified Method in the Literature.[12e,15b,23] The manipulations were carried out on a Schlenk line with high-purity nitrogen. A solution of NH_3BH_3 (2.48 g, 80 mmol) in THF (40 mL) was slowly added to the solution of NaH (0.96 g, 40 mmol) in THF (40 mL). Gas slowly evolved, the mixture was then heated to reflux for 10 h, and a white solid was formed. After the solution was cooled to room temperature, n-hexane (80 mL) was added, and the reaction mixture was filtered to provide pure NaADBH as a white solid (1.29 g, 19.25 mmol, 48%).[11]B NMR (193 MHz, DMSO-d_6) δ −19.92 (q, J_{B-H} = 89.5 Hz).

Stability of $NaNH_2(BH_3)_2$ in THF Solution at Room Temperature. To examine the stability of $NaNH_2(BH_3)_2$ in the THF solution at room temperature, we used 0.0067 g of (0.1 mmol) $NaNH_2(BH_3)_2$ in 0.5 mL of THF in an NMR tube. The results show that its THF solution is stable for several days (Figure S1).

Determination of the Forming NH_2BH_2 Byproduct in the Reaction Captured by Cyclohexene. A sample of 1 mL of 0.36 M THF solution of $NaNH_2(BH_3)_2$ (24 mg, 0.36 mmol) was added to the mixture of 0.5 mL of 0.4 M cinnamic acid (30 mg, 0.2 mmol) and 36 μL of cyclohexene (30 mg, 0.36 mmol, 1.0 equiv) solution in THF at room temperature. The generation of aminoborane NH_2BH_2 in the reaction was captured by the addition of cyclohexene to form the organoborane Cy_2BNH_2 (Scheme S1) whose characteristic appeared at δ 47.70 ppm in ^{11}B NMR (Figure S2).[24] However, it is proved that NH_2BH_2 determined here is from the catalyzed decomposition of $NaNH_2(BH_3)_2$ (see Figure S6).

Determination of Forming $NH_2B_2H_5$ in the Reaction System. A sample of 1 mL of 0.36 M THF solution of $NaNH_2(BH_3)_2$ (24 mg, 0.36 mmol) was added to 0.5 mL of 0.4 M benzyl acid (24 mg, 0.20 mmol) in THF solution at −40 °C. The mixture was kept at −40 °C for 1 h and then warmed to room temperature. NMR was rapidly recorded, in which the forming $Na[PhC(O)OBH_2NH_2BH_3]$ and $NH_2B_2H_5$ (ADB) were detected by ^{11}B and $^{11}B\{H\}$NMR (Figure S3). The formation of $NH_2B_2H_5$ is from the first stage of the reaction, as discussed in text (Scheme S2 and Figure 2).

Determination of Forming H_2 in the Reaction. A sample of 10 mL of 0.36 M THF solution of $NaNH_2(BH_3)_2$ (240 mg, 3.6 mmol) was added to 5 mL of 0.4 M cinnamic acid (296 mg, 2 mmol) in THF solution at room temperature. The forming gas was passed through C_6D_6, and then, the solution of C_6D_6 was determined by ^{1}H NMR spectroscopy (Figure S4).

$NH_2B_2H_5$-Catalyzed Decomposition of $NaNH_2(BH_3)_2$ to $NaBH_4$ and NH_2BH_2 Polymers. A sample of 1 mL of 0.4 M THF solution of $NH_2B_2H_5$ (17 mg, 0.4 mmol) was added into 10 mL of 0.4 M THF solution of $NaNH_2(BH_3)_2$ (268 mg, 4.0 mmol) at −40 °C (Scheme S3), which was monitored by ^{11}B NMR spectroscopy ((a) in Figure S5), in comparison with the same concentration THF solution of $NaNH_2(BH_3)_2$ in the absence of $NH_2B_2H_5$ ((b) in Figure S5).

Determination of Forming NH_2BH_2 in the $NH_2B_2H_5$-Catalyzed Decomposition of $NaNH_2(BH_3)_2$. A sample of 1 mL of 0.36 M THF solution of the $NH_2B_2H_5$ (15 mg, 0.36 mmol) solution was added to the mixture of 1 mL of 0.36 M $NaNH_2(BH_3)_2$ (24 mg, 0.36 mmol) and 36 μL of cyclohexene (30 mg, 0.36 mmol) solution in THF at room temperature. The mixture was monitored by ^{11}B NMR (Figure S6) in which the characteristic peak of Cy_2BNH_2 appeared at δ 47.56 ppm.

Simulation of the Decomposition of $NaNH_2(BH_3)_2$ Catalyzed by $NH_2B_2H_5$. The decomposition of $NaNH_2(BH_3)_2$ catalyzed by $NH_2B_2H_5$ to form NH_2BH_2 and $NaBH_4$ was simulated, and the results are shown in Figure S7. THF reacts with $NH_2B_2H_5$ to form $THFBH_3$ and NH_2BH_2 via transition state TS01 with an energy barrier of 22.6 kcal/mol. Then, $THFBH_3$ reacts with $BH_3NH_2BH_3^-$ to generate $NH_2B_2H_5$ and BH_4^- via transition states TS02 and TS03, whose energy barriers are 18.3 and 9.1 kcal/mol, respectively.

Reaction of $THFBH_3$ and $NaNH_2(BH_3)_2$ Forming $NH_2B_2H_5$ and $NaBH_4$. On the basis of these calculation results (Figure S7), it is found that $THFBH_3$ reacts with $NaNH_2(BH_3)_2$ to afford $NaBH_4$ and $NH_2B_2H_5$ (Scheme S4); thus, the following experiment was carried out. A sample of 0.1 mL of 1 M $THFBH_3$ solution (0.1 mmol) was added to 1 mL of 0.1 M $NaNH_2(BH_3)_2$ (0.1 mmol) in THF at −40 °C. The mixture was detected by ^{11}B NMR (Figure S8) in which the forming $NH_2B_2H_5$ and $NaBH_4$ appeared at δ −27.28 ppm and δ −43.27 ppm, respectively. A small amount of NH_3BH_3 was also observed.

Reaction of the Forming $NaNH_2BH_3$ and the Hydroxyl-Substituted Substrate to Afford NH_3BH_3 and the Corresponding Sodium Salt. To a sample of 1 mL of 0.36 M THF solution of $NaNH_2(BH_3)_2$ (24 mg, 0.36 mmol) solution was added 0.5 mL of 0.4

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M THF solution of 4-hydroxybenzyl acid (28 mg, 0.2 mmol) at room temperature. The reaction mixture was monitored by ^{11}B NMR, in which the forming ammonia borane (NH_3BH_3, AB) was detected (top, Figure S9). The forming NH_3BH_3 was confirmed by the addition of an authentic NH_3BH_3 sample (bottom, Figure S9).

Determination of the Hydroboration Products and the Hydrolysis Products of the Reaction of Cinnamic Acid and $NaNH_2(BH_3)_2$. A sample of 10 mL of 0.36 M THF solution of $NaNH_2(BH_3)_2$ (240 mg, 3.6 mmol) was added to 5 mL of 0.4 M THF solution of cinnamic acid (296 mg, 2 mmol) at room temperature. After 2.5 h, the reaction mixture was filtrated, and the solvent was removed from filtration. The residue was extracted using toluene, and then, the toluene was removed (Scheme S5). The reaction mixture was monitored by NMR spectroscopy in which the forming $NaNH_2BH_3$ and alkylborates were detected by ^{11}B and ^{11}B{^{1}H} NMR (Figures S10 and S11) and ^{1}H and ^{1}H{^{11}B} NMR (Figures S12 and S13), and were also characterized by ^{13}C{^{1}H} NMR (Figure S14) in CD_3CN. Then, 0.1 mL of D_2O was added to the solution. AB and the corresponding alcohols were confirmed by ^{11}B and ^{11}B{^{1}H} NMR (Figures S15 and S16) and ^{1}H and ^{1}H{^{11}B} NMR (Figures S17 and S18), and were also characterized by ^{13}C{^{1}H} NMR (Figure S19).

Determination of the Hydroboration Products and the Hydrolysis Products of the Reaction of Benzyl Acid and $NaNH_2(BH_3)_2$. A sample of 10 mL of 0.36 M THF solution of $NaNH_2(BH_3)_2$ (240 mg, 3.6 mmol) was added to 5 mL of 0.4 M THF solution of benzyl acid (244 mg, 2 mmol) at room temperature. After 1 h, the reaction mixture was filtrated, and the solvent was removed from filtration. The residual was extracted using toluene, and then, the toluene was removed (Scheme S6). The reaction mixture was monitored by NMR spectroscopy in which the forming $NaNH_2BH_3$ and alkylborates were detected by ^{11}B and ^{11}B{^{1}H} NMR (Figures S20 and S21) and ^{1}H and ^{1}H{^{11}B} NMR (Figures S22 and S23), and they were also characterized by ^{13}C{^{1}H} NMR (Figure S24) in CD_3CN. Then, 0.1 mL of D_2O was added to the solution. AB and the corresponding alcohols were confirmed by ^{11}B and ^{11}B{^{1}H} NMR (Figures S25 and S26) and ^{1}H and ^{1}H{^{11}B} NMR (Figures S27 and S28), and they were also characterized by ^{13}C{^{1}H} NMR (Figure S29).

Determination of the Reactant Molar Ratio. To examine how many hydrides in $NaNH_2(BH_3)_2$ can take part in the reaction because $NaNH_2(BH_3)_2$ contains six negatively charged hydrogens (B−H), we designed 1 equiv $NaNH_2(BH_3)_2$ (134 mg, 2.0 mmol) to reduce 1 equiv cinnamic acid (296 mg, 2.0 mmol) to cinnamyl alcohol. The conversion is about 39% on the basis of the integral value in ^{1}H NMR (Figure S30).

Reaction of Phenol and $NaNH_2BH_3$. In order to confirm that $NaNH_2BH_3$ can abstract the proton from the hydroxyl group of phenol, the following experiment was carried out. A sample of 1 mL of 0.4 M THF solution of $NaNH_2BH_3$ (27 mg, 0.4 mmol) was added to 1 mL of 0.4 M phenol (38 mg, 0.4 mmol) in THF at room temperature (Scheme S7). The reaction mixture was monitored by ^{11}B NMR in which the forming NH_3BH_3 was detected (Figure S31) and further confirmed by the addition of authentic NH_3BH_3 into the mixture (Figure S32).

Reduction of Carboxylic Acid Derivatives and Nitriles with NaADBH. A sample of 5 mL of 0.2 M THF solution of $NaNH_2(BH_3)_2$ (67 mg, 1 mmol) was added to 5 mL of 0.2 M THF solution of benzoyl chloride (141 mg, 1 mmol) at room temperature. After 0.5 h, the hydrolysis of borate esters was carried out by the addition of excess water, forming the corresponding alcohol and trimethylborate, and the reaction mixture was extracted with ethyl acetate (3 × 20 mL) and dichloromethane (3 × 20 mL). The combined organic extracts were dried over anhydrous Na_2SO_4 and concentrated by rotary evaporation, and the residue was purified by silica gel column chromatography to obtain the colorless liquid product phenylmethanol (gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; 0.0886 g, 82%). **^{1}H NMR (400 MHz, $CDCl_3$)** δ: 7.39−7.29 (m, 5 H), 4.53 (s, 2H), 2.54 (br, s, 1H); **^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)** δ: 140.9, 128.6, 127.7, 127.0, 65.1.

A sample of 10 mL of 0.2 M THF solution of $NaNH_2(BH_3)_2$ (134 mg, 2 mmol) was added to 5 mL of 0.2 M THF solution of methyl 3-phenylpropionate (164 mg, 1 mmol) at room temperature and then refluxed. After 2 h, the hydrolysis of borate esters was carried out by the addition of excess water, forming the corresponding alcohol and trimethylborate, and the reaction mixture was extracted with ethyl acetate (3 × 20 mL) and dichloromethane (3 × 20 mL). The combined organic extracts were dried over anhydrous Na_2SO_4 and concentrated by rotary evaporation, and the residue was purified by silica gel column chromatography to obtain the colorless liquid product 3-phenylpropan-1-ol (gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; 0.1197 g, 88%). **^{1}H NMR (400 MHz, $CDCl_3$)** δ 7.34−7.28 (m, 2H), 7.25−7.18 (m, 3H), 3.68 (t, J = 6.5 Hz, 2H), 2.76−2.64 (m, 2H), 1.96−1.87 (m, 2H), 1.77 (br, s, 1H). **^{13}C{^{1}H} (101 MHz, $CDCl_3$)** δ 141.9, 128.5, 128.5, 125.9, 62.3, 34.3, 32.2.

A sample of 15 mL of 0.2 M THF solution of $NaNH_2(BH_3)_2$ (134 mg, 2 mmol) was added to 5 mL of 0.2 M THF solution of benzonitrile (103 mg, 1 mmol) at room temperature and then refluxed. After 2 h, the hydrolysis of borate esters was carried out by the addition of excess water, forming the corresponding amine and trimethylborate, and the reaction mixture was extracted with ethyl acetate (3 × 20 mL) and dichloromethane (3 × 20 mL). The combined organic extracts were dried over anhydrous Na_2SO_4 and concentrated by rotary evaporation, and the residue was purified by silica gel column chromatography to obtain the colorless liquid product phenylmethanamine (gradient eluent: EtOAc/petroleum ether: 1/2 to 1/1; 0.0751 g, 70%). **^{1}H NMR (400 MHz, $CDCl_3$)** δ: 7.33−7.26 (m, 4 H), 7.23−7.20 (m, 1 H), 3.83−3.81 (m, 2 H), 1.56 (br, s, 2H); **^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)** δ: 143.2, 128.4, 127.0, 126.7, 46.4.

General Experimental Procedure for the Hydroboration Reactions of Various Carboxylic Acids with NaADBH. A solution of NaADBH (3.6 mmol) in THF (10 mL) was added to the solution of carboxylic acid (2.0 mmol) in THF (5 mL) at room temperature under an air atmosphere. The gas evolved fast, and the formation of a white precipitate was observed during the reaction. The progress of the reaction was monitored by TLC. Upon completion, the hydrolysis of borate esters was carried out by the addition of excess water, forming the corresponding alcohols and boric acid, and the reaction mixture was extracted with ethyl acetate (3 × 20 mL) and dichloromethane (3 × 20 mL). The combined organic extracts were dried over anhydrous Na_2SO_4 and concentrated by rotary evaporation, and the residue was purified by silica gel column chromatography to obtain the product. The characterization data and the ^{1}H and ^{13}C NMR spectra of all the forming alcohol products are listed in the Supporting Information.

*Cinnamyl Alcohol (**2a**).*[25] Colorless liquid; yield: 241 mg, 90%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (400 MHz, $CDCl_3$)** δ: 7.34−7.12 (m, 5H), 6.53 (d, J = 15.9 Hz, 1H), 6.28 (dt, J = 15.9, 5.7 Hz, 1H), 4.23 (d, J = 7.2 Hz, 2H), 1.75 (br, s, 1H); **^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$)** δ: 136.7, 131.2, 128.6, 128.5, 127.7, 126.5, 63.5.

*Benzyl Alcohol (**2b**).*[26] Colorless liquid; yield: 156 mg, 72%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (600 MHz, $CDCl_3$)** δ: 7.55−6.97 (m, 5 H), 4.61 (s, 2 H), 2.94 (br, s, 1H); **^{13}C{^{1}H} NMR (151 MHz, $CDCl_3$)** δ: 140.9, 128.6, 127.7, 127.0, 65.2.

*(4-Fluorophenyl)methanol (**2c**).*[27] colorless liquid; yield: 181 mg, 72%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (600 MHz, DMSO-d_6)** δ: 7.37−7.34 (m, 2H), 7.15−7.12 (m, 2H), 5.30 (s, 1H), 4.49 (s, 2H); **^{13}C{^{1}H} NMR (151 MHz, DMSO-d_6)** δ: 161.6 (d, $^1J_{C\text{-}F}$ = 241.7 Hz), 139.1 (d, $^4J_{C\text{-}F}$ = 2.9 Hz), 128.8 (d, $^3J_{C\text{-}F}$ = 8.1 Hz), 115.2 (d, $^2J_{C\text{-}F}$ = 21.1 Hz), 62.7; **^{19}F NMR (576 MHz, DMSO-d_6)** δ: −116.49.

*(4-Chlorophenyl)methanol (**2d**).*[28] White solid; yield: 261 mg, 92%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (600 MHz, DMSO-d_6)** δ: 7.35 (dd, J = 26.9, 8.3 Hz, 4H), 5.27 (t, J = 5.7 Hz, 1H), 4.48 (d, J = 5.7 Hz, 2H); **^{13}C{^{1}H} NMR (151 MHz, DMSO-d_6)** δ: 142.1, 131.5, 128.7, 128.5, 62.6.

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(4-Bromophenyl)methanol (2e).[25] White solid; yield: 335 mg, 90%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (600 MHz, DMSO-d$_6$)** δ: 7.51 (d, J = 8.4 Hz, 2H), 7.27 (d, J = 8.4 Hz, 2H), 5.26 (t, J = 5.7 Hz, 1H), 4.46 (d, J = 5.6 Hz, 2H); **^{13}C{^{1}H} NMR (151 MHz, DMSO-d$_6$)** δ: 142.5, 131.4, 129.0, 120.0, 62.6.

(4-Iodophenyl)methanol (2f).[25] White solid; yield: 421 mg, 90%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (600 MHz, DMSO-d$_6$)** δ: 7.61 (d, J = 8.2 Hz, 2H), 7.06 (d, J = 8.2 Hz, 2H), 5.17 (t, J = 5.7 Hz, 1H), 4.38 (d, J = 5.7 Hz, 2H); **^{13}C{^{1}H} NMR (151 MHz, DMSO-d$_6$)** δ: 142.9, 137.2, 129.2, 92.7, 62.7.

2-Methylbenzyl Alcohol (2g).[29] Colorless liquid; yield: 220 mg, 90%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (600 MHz, CDCl$_3$)** δ: 7.38−7.32 (m, 1H), 7.25−7.20 (m, 2H), 7.20−7.16 (m, 1H), 4.67 (s, 2H), 2.35 (s, 3H), 2.07 (br, s, 1H); **^{13}C{^{1}H} NMR (151 MHz, CDCl$_3$)** δ: 138.8, 136.2, 130.4127.9, 127.6, 126.1, 63.5, 18.7.

2-Methoxybenzyl Alcohol (2h).[30] Colorless liquid; yield: 207 mg, 75%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (400 MHz, CDCl$_3$)** δ: 7.16 (t, J = 7.9 Hz, 2H), 6.83 (t, J = 7.4 Hz, 1H), 6.76 (d, J = 8.3 Hz, 1H), 4.56 (s, 2H), 3.72 (s, 3H), 2.58 (s, 1H). **^{13}C{^{1}H} NMR (101 MHz, CDCl$_3$)** δ: 157.4, 129.2, 128.9, 128.7, 120.7, 110.2, 61.8, 55.3.

2-Hydroxybenzyl Alcohol (2i).[31] White solid; yield: 174 mg, 70%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (600 MHz, CDCl$_3$)** δ: 7.21 (t, J = 7.7 Hz, 1H), 7.03 (d, J = 7.4 Hz, 1H), 6.92−6.82 (m, 2H), 4.86 (s, 2H), 2.28 (s, 1H); **^{13}C{^{1}H} NMR (151 MHz, CDCl$_3$)** δ: 156.1, 129.6, 127.9, 124.6, 120.1, 116.6, 64.7.

2-Nitrobenzyl Alcohol (2j).[27] White solid; yield: 282 mg, 92%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (600 MHz, CDCl$_3$)** δ: 8.09 (d, J = 8.2 Hz, 1H), 7.74 (d, J = 7.7 Hz, 1H), 7.67 (dd, J = 10.8, 4.3 Hz, 1H), 7.47 (dd, J = 11.3, 4.2 Hz, 1H), 4.97 (s, 2H), 2.72 (s, 1H); **^{13}C{^{1}H} NMR (151 MHz, CDCl$_3$)** δ: 146.6, 135.8, 133.1, 128.9, 127.5, 124.0, 61.5.

3-Methylbenzyl Alcohol (2k).[32] Colorless liquid; yield: 212 mg, 87%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (600 MHz, CDCl$_3$)** δ: 7.26 (t, J = 7.5 Hz, 1H), 7.19 (s, 1H), 7.16 (d, J = 7.5 Hz, 1H), 7.12 (d, J = 7.5 Hz, 1H), 4.65 (s, 2H), 2.56 (br, s, 1H), 2.37 (s, 3H); **^{13}C{^{1}H} NMR (151 MHz, CDCl$_3$)** δ: 140.9, 138.3, 128.6, 128.5, 127.9, 124.2, 65.4, 21.5.

3-Methoxybenzyl Alcohol (2l).[32] Colorless liquid; yield: 215 mg, 78%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (400 MHz, CDCl$_3$)** δ: 7.17 (t, J = 8.1 Hz, 1H), 6.83 (d, J = 7.6 Hz, 2H), 6.73 (d, J = 11.2 Hz, 1H), 4.54 (s, 2H), 3.71 (s, 3H), 2.26 (br, s, 1H); **^{13}C{^{1}H} NMR (101 MHz, CDCl$_3$)** δ: 159.8, 142.7, 129.6, 119.1, 113.2, 112.3, 64.9, 55.0.

3-Nitrobenzyl Alcohol (2m).[27] White solid; yield: 214 mg, 70%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (400 MHz, CDCl$_3$)** δ: 8.13 (d, J = 9.3 Hz, 1H), 8.03 (t, J = 8.8 Hz, 1H), 7.61 (t, J = 7.1 Hz, 1H), 7.45 (q, J = 8.2 Hz, 1H), 4.72 (s, 2H), 3.54 (br, s, 1H); **^{13}C{^{1}H} NMR (101 MHz, CDCl$_3$)** δ: 148.2, 143.0, 132.8, 129.4, 122.3, 121.3, 63.6.

4-Tolylmethanol (2n).[28] Yield: white solid; 220 mg, 90%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (600 MHz, DMSO-d$_6$)** δ: 7.19 (d, J = 7.8 Hz, 2H), 7.12 (d, J = 7.8 Hz, 2H), 5.09 (t, J = 5.7 Hz, 1H), 4.44 (d, J = 5.7 Hz, 2H), 2.28 (s, 3H); **^{13}C{^{1}H} NMR (151 MHz, DMSO-d$_6$)** δ: 134.0, 136.0, 129.1, 127.0, 63.2, 21.2.

4-tert-Butylbenzyl Alcohol (2o).[28] Colorless liquid; yield: 262 mg, 80%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (600 MHz, DMSO-d$_6$)** δ: 7.11 (d, J = 8.3 Hz, 2H), 6.99 (d, J = 8.4 Hz, 2H), 4.30 (s, 2H), 1.06 (s, 9H); **^{13}C{^{1}H} NMR (151 MHz, DMSO-d$_6$)** δ: 149.5, 140.0, 126.8, 125.2, 63.2, 34.6, 31.7.

4-Methoxybenzyl Alcohol (2p).[27] Colorless liquid; yield: 215 mg, 78%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (600 MHz, DMSO-d$_6$)** δ: 7.10 (d, J = 8.4 Hz, 2H), 6.73 (d, J = 8.5 Hz, 2H), 4.38 (s, 2H), 3.64 (s, 3H); **^{13}C{^{1}H} NMR (151 MHz, DMSO-d$_6$)** δ: 158.7, 135.0, 128.4, 113.9, 63.1, 55.4.

4-Hydroxybenzyl Alcohol (2q).[31] White solid; yield: 174 mg, 70%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (400 MHz, DMSO-d$_6$)** δ: 9.22 (s, 1H), 7.10 (d, J = 8.1 Hz, 2H), 6.70 (d, J = 8.0 Hz, 2H), 4.94 (t, J = 5.2 Hz, 1H), 4.36 (d, J = 4.9 Hz, 2H); **^{13}C{^{1}H} NMR (101 MHz, DMSO-d$_6$)** δ: 156.6, 133.2, 128.5, 115.2, 63.2.

4-Cyanobenzyl alcohol (2r).[33] Colorless liquid; yield: 239 mg, 90%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (600 MHz, DMSO-d$_6$)** δ: 7.79 (d, J = 7.9 Hz, 2H), 7.51 (d, J = 8.4 Hz, 2H), 5.46 (t, J = 5.7 Hz, 1H), 4.59 (d, J = 5.5 Hz, 2H); **^{13}C{^{1}H} NMR (151 MHz, DMSO-d$_6$)** δ: 149.0, 132.5, 127.4, 119.5, 109.8, 62.7.

4-Nitrobenzyl Alcohol (2s).[34] White solid; yield: 275 mg, 90%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (600 MHz, DMSO-d$_6$)** δ: 8.20 (d, J = 8.7 Hz, 1 H), 7.59 (d, J = 8.5 Hz, 1H), 5.53 (s, 1H), 4.64 (s, 1H); **^{13}C{^{1}H} NMR (151 MHz, DMSO-d$_6$)** δ: 151.3, 127.5, 123.8, 62.5.

1,4-Benzenedimethanol (2t).[35] White solid; yield: 248 mg, 90%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (600 MHz, DMSO-d$_6$)** δ: 7.25 (s, 4H), 5.12 (t, J = 5.7 Hz, 2H), 4.47 (d, J = 5.7 Hz, 4H); **^{13}C{^{1}H} NMR (151 MHz, DMSO-d$_6$)** δ: 141.3, 126.7, 63.2.

1-Naphthalenemethanol (2u).[27] White solid, yield: 275 mg, 87% **^{1}H NMR (600 MHz, DMSO-d$_6$)** δ: 8.10 (d, J = 7.8 Hz, 1H), 7.94 (d, J = 7.6 Hz, 1H), 7.83 (d, J = 8.2 Hz, 1H), 7.54−7.48 (m, 4H), 5.31 (s, 1H), 4.99 (s, 2H); **^{13}C{^{1}H} NMR (151 MHz, DMSO-d$_6$)** δ: 138.3, 133.6, 131.2, 128.8, 127.7, 126.3, 126.1, 125.9, 124.7, 124.2, 61.6.

1,4-Benzenedimethanol (2v).[35] White solid; yield: 248 mg, 90%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (600 MHz, DMSO-d$_6$)** δ: 7.25 (s, 4H), 5.12 (t, J = 5.7 Hz, 2H), 4.47 (d, J = 5.7 Hz, 4H); **^{13}C{^{1}H} NMR (151 MHz, DMSO-d$_6$)** δ: 141.3, 126.7, 63.2.

3-Phenylpropan-1-ol (2w).[25] Colorless liquid; yield: 245 mg, 90%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (600 MHz, DMSO-d$_6$)** δ: 7.27 (t, J = 7.6 Hz, 2H), 7.23−7.12 (m, 3H), 4.46 (s, 1H), 3.43−3.41 (m, 2H), 2.61 (t, J = 7.7 Hz, 2H), 1.74−1.69 (m, 2H); **^{13}C{^{1}H} NMR (151 MHz, DMSO-d$_6$)** δ: 142.7, 128.7 (d, J = 9.1 Hz), 126.1, 60.6, 34.8, 32.1.

1-Phenylbutane-1,4-diol (2x).[36] Colorless liquid; yield: 239 mg, 72%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (600 MHz, DMSO-d$_6$)** δ: 7.81−6.64 (m, 5H), 5.12 (d, J = 3.8 Hz, 1H), 4.51 (d, J = 5.3 Hz, 1H), 4.36 (t, J = 4.6 Hz, 1H), 3.37 (dd, J = 11.2, 5.6 Hz, 2H), 1.66−1.55 (m, 2H), 1.54−1.28 (m, 2H); **^{13}C{^{1}H} NMR (151 MHz, DMSO-d$_6$)** δ: 146.9, 128.4, 127.0, 126.3, 72.7, 61.3, 36.4, 29.5.

Butane-1,4-diol (2y).[37] Yield: colorless liquid; 144 mg, 80%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (600 MHz, CDCl$_3$)** δ: 3.62 (t, J = 5.8 Hz, 4H), 2.28 (s, 2H), 1.64−1.61 (m, 4H); **^{13}C{^{1}H} NMR (151 MHz, CDCl$_3$)** δ: 62.6, 29.8.

Decane-1,10-diol (2z).[38] White solid; yield: 341 mg, 98%; gradient eluent: EtOAc/petroleum ether: 1/4 to 1/2; **^{1}H NMR (400 MHz, CDCl$_3$)** δ: 3.64 (t, J = 6.6 Hz, 4H), 1.68−1.50 (m, 4H), 1.42 (br, s, 2H), 1.30 (br, s, 12H); **^{13}C{^{1}H} NMR (101 MHz, CDCl$_3$)** δ: 63.1, 32.8, 29.5,29.4, 25.7.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.joc.1c00302.

Details for experiments, characterizations, and computations (PDF)

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Notes

The authors declare no competing financial interest.

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