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Regio- and Stereoselective Nickel-Catalyzed Homoallylation of Aldehydes with 1,3-Dienes

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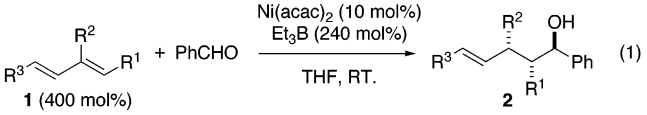
Abstract: $Ni(acac)_2$ catalyzes homoallylation of aldehydes with 1,3-dienes in the presence of triethylborane. Triethylborane serves as a reducing agent delivering a formal hydride to the C2 position of 1,3-dienes, thus generating a formal homoallyl anion species and enabling the novel homoallylation of aldehydes. The reaction proceeds smoothly at room temperature in the absence of any phosphane or nitrogen ligands and is highly regioselective and stereoselective for a wide variety combination of aldehydes and 1,3-dienes: e.g., isoprene and benzaldehyde combine to give a mixture of *anti*- and *syn*-1-phenyl-3-methyl-4-penten-1-ol (**2.2**) in a ratio of 15:1 in 90% yield. Under the conditions, sterically congested aliphatic aldehydes and ketones show low yields. In such cases, diethylzinc serves as a substitute for triethylborane and yields the expected products in good yields with similarly high regio- and stereoselectivity. 1,3-Cyclohexadiene is one exception among 24 kinds of dienes examined and undergoes allylation (not homoallylation) selectively.

Introduction

Organonickel complexes are distinctive in their nucleophilic reactivity from organometal complexes of the other group 10 elements.[1] Nucleophilic allylation of carbonyl compounds[2] and alkyl halides[3] with π-allyl nickels has proved to be particularly useful and has been utilized widely for the synthesis of natural and unnatural products. Unfortunately, however, this methodology requires a stoichiometric amount of nickel.

Recently, useful versions of nickel-catalyzed allylation and vinylation of aldehydes with 1,3-dienes[4] and alkynes,[5] allenes,[6] and alkenes[7] have been developed, which provide useful access to homoallyl alcohols and allyl alcohols, respectively.[1a,b] Compared with the catalytic allylation and vinylation, however, only a limited number of homoallylation reaction regarding the nickel[8] and other transition metal catalyses[9] have been reported so far. This is probably owing to the difficult availability and the low nucleophilicity of homoallylic transition metal species.

In 1998, we disclosed for the first time that $Ni(acac)_2$ [acac = acetylacetonato] was able to promote the catalytic homoallylation of benzaldehyde with a variety of 1,3-dienes in the presence of triethylborane, stereoselectively yielding bis-homoallyl alcohols *anti*-**2** (eq 1).[10]



1 (400 mol%) **2** (1)

† Graduate School of Science and Technology, Nagasaki University.

(1) (a) Tamaru, Y., Ed. *Modern Organic Chemistry*; Wiley-VCH: Weinheim, 2005. (b) Montgomery, J. *Angew. Chem., Int. Ed.* **2004**, *43*, 3890−3908. (c) Tsuji, J. *Transition Metal Regents and Catalysts*; Wiley & Sons: Chichester, 2000. (d) Davies, S. G. *Organotransition Metal Chemistry: Application to Organic Synthesis*; Pergamon: Oxford, 1982; Chapter 6.
(2) Semmelhack, M. F. *Organic Reactions*; Wiley: New York, 1972; Vol. 19, Chapter 2.
(3) (a) Hegedus, L. S.; Varaprath, S. *Organometallics* **1982**, *1*, 259−263. (b) Semmelhack, M. F.; Wu, E. S. C. *J. Am. Chem. Soc.* **1976**, *98*, 3384−3386.
(4) (a) Kojima, K.; Kimura, M.; Tamaru, Y. *Chem. Commun.* **2005**, 4717−4719. (b) Kimura, M.; Ezoe, A.; Mori, M.; Tamaru, Y. *J. Am. Chem. Soc.* **2005**, *127*, 201−209. (c) Kimura, M.; Kojima, K.; Inoue, T.; Tamaru, Y. *Synthesis* **2004**, 3089−3091. (d) Ezoe, A.; Kimura, M.; Inoue, T.; Mori, M.; Tamaru, Y. *Angew. Chem., Int. Ed.* **2002**, *41*, 2784−2786. (e) Sato, Y.; Saito, N.; Mori, M. *J. Org. Chem.* **2002**, *67*, 9310−9317. (f) Shibata, K.; Kimura, M.; Kojima, K.; Tanaka, S.; Tamaru, Y. *J. Organomet. Chem.* **2001**, *624*, 348−353. (g) Kimura, M.; Shibata, K.; Koudahashi, Y.; Tamaru, Y. *Tetrahedron Lett.* **2000**, *41*, 6789−6793. (h) Kimura, M.; Matsuo, S.; Shibata, K.; Tamaru, Y. *Angew. Chem., Int. Ed.* **1999**, *38*, 3386-3388. (i) Sato, Y.; Saito, N.; Mori, M. *Tetrahedron* **1998**, *54*, 1153−1168. (j) Takimoto, M.; Hiraga, Y.; Sato, Y.; Mori, M. *Tetrahedron Lett.* **1998**, *39*, 4543−4546. (k) Sato, Y.; Takimoto, M.; Hayashi, K.; Katsuhara, T.; Takagi, K.; Mori, M. *J. Am. Chem. Soc.* **1994**, *116*, 9771−9772.
(5) (a) Knapp-Reed, B.; Mahandru, G. M.; Montgomery, J. *J. Am. Chem. Soc.* **2005**, *127*, 13156−13157. (b) Mahandru, G. M.; Liu, G.; Montgomery, J. *J. Am. Chem. Soc.* **2004**, *126*, 3698−3699. (c) Patel, S. J.; Jamison, T. F. *Angew. Chem., Int. Ed.* **2004**, *43*, 3941−3944. (d) Miller, K. M.; Lanphaisarnnont, T.; Molinaro, C.; Jamison, T. F. *J. Am. Chem. Soc.* **2004**, *126*, 4130−4131.
(6) (a) Ng, S.-S.; Jamison, T. F. *J. Am. Chem. Soc.* **2005**, *127*, 7320−7321. (b) Montgomery, J.; Song, M. *Org. Lett.* **2002**, *4*, 4009−4011.
(7) Ng, S.-S.; Jamison, T. F. *J. Am. Chem. Soc.* **2005**, *127*, 14194−14195.
(8) Catalytic with respect to Ni: (a) Sato, Y.; Takimoto, M.; Mori, M. *J. Am. Chem. Soc.* **2000**, *122*, 1624−1634. Stoichiometric with respect to Ni: (b) Sato, Y. Takimoto, M.; Mori, M. *Synlett* **1997**, 734−736. (c) Sato, Y.; Takimoto, M.; Mori, M. *Tetrahedron Lett.* **1996**, *37*, 887−890.
(9) Catalytic with respect to Rh: Kong, J.-R.; Ngai, M.-Y.; Krische, M. J. *J. Am. Chem. Soc.* **2006**, *128*, 718−719 and references therein. (b) Jang, H.-Y.; Krische, M. J. *Eur. J. Org. Chem.* **2004**, 3953−3958. Stoichiometric with respect to Zr: (b) Yasuda, H.; Tatsumi, K.; Nakamura, A. *Acc. Chem. Res.* **1985**, *18*, 120−126. (c) Erker, G.; Engel, K.; Atwood, J. L.; Hunter, W. E. *Angew. Chem., Int. Ed. Engl.* **1983**, *22*, 494−495. (d) Erker, G.; Dorf, U. *Angew. Chem., Int. Ed. Engl.* **1983**, *22*, 777−778. (e) Bertelo, C. A.; Schwartz, J. *J. Am. Chem. Soc.* **1976**, *98*, 262−264.
(10) Kimura, M.; Ezoe, A.; Shibata, K.; Tamaru, Y. *J. Am. Chem. Soc.* **1998**, *120*, 4033−4034.

Subsequently, we have also demonstrated that (1) a similar homoallylation reaction is successful for aliphatic aldehydes and ketones by making use of diethylzinc (Et_2Zn)[11] and (2) the reaction with Et_3B is compatible with water and even promotes the homoallylation of commercial 50% aqueous glutaraldehyde and ω-hydroxyaldehydes (lactols).[12] All these reactions generally proceed at room temperature or below without using any phosphane or amine ligands and show excellent 1,2-*anti*- ($R^1 \neq H$) and 1,3-*anti*-selectivity ($R^2 \neq H$) (eq 1). The Et_2Zn-Ni catalytic system has been successfully extended to the homoallylation of the less reactive aldimines, which shows an opposite stereoselectivity and provides 1,3-*syn*-bishomoallylamines in excellent yields.[13]

This article describes a full scope of the homoallylation reaction of a variety of combinations of dienes (24 kinds) and aromatic, unsaturated, and aliphatic aldehydes (18 kinds) and ketones (6 kinds).[10,11] The most remarkable aspects, newly developed and, demonstrated here, are that (1) some dienes, bearing electron-donating substituents, such as $OSiR_3$ and OMe, not only provide **2** of useful levels of oxidation states and molecular functional arrays but also show marked difference in reactivity as large as 15 000 times, depending on the substitution position at either C1 or C2 of dienes and (2) cyclohexadiene is exceptional among dienes examined and selectively furnishes allylation products, not homoallylation products. Furthermore, the reaction conditions were modified so as to be applicable to a 10-g scale preparation of **2**. Aldehydes possessing stereocenters at the α- or β-positions showed almost no diastereofacial selectivity, i.e. the present homoallylation does not follow the Cram model (or Felkin-Ahn model).

In the present homoallylation, a formal hydride that stems from the methyl group of Et_3B or Et_2Zn is delivered regio- and stereoselectively at the C2 positions of 1,3-dienes. The origin of the regioselective hydride delivery at the C2 position rather than at the allylically related C4 position of 1,3-dienes is addressed. Furthermore, mechanistic rationale is given for the 1,2- and 1,3-diastereostereoselectivity and the enormous difference in the relative reactivity among dienes (e.g., 2-siloxy-1,3-diene (**1r**)/1-siloxy-1,3-diene (**1u**) = 15 000) as well as unusual reactivity that cyclohexadiene displays.

Results and Discussion

1. Homoallylation of Aromatic and α,β-Unsaturated Aldehydes with Dienes Promoted with Et_3B. The reactions of benzaldehydes with parent 1,3-butadiene (**1a**) and alkyl- and aryl-substituted dienes **1b**−**q** are summarized in Table 1, and those with alkoxy-substituted dienes **1r**−**x** in Table 2. These reactions are performed uniformly at room temperature under N_2 using a diene (4 mmol), benzaldehyde (1 mmol), $Ni(acac)_2$ (0.1 mmol), and Et_3B (2.4 mmol, 1 M in hexane) in THF (5 mL).

As for the reaction site (regioselectivity) of unsymmetrical dienes, Table 1 clearly indicates that C2 electron-donating substituents (e.g., Me, CH_2SiMe_3) strongly favor the reaction at the C1 butadiene terminal, giving rise to **2** exclusively (runs 2, 3, and 5), whereas C2 phenyl substituent does not, furnishing a mixture of C1- and C4-coupling products in ∼10 to 1 ratio

Table 1. Ni^0-Catalyzed Homoallylation of Benzaldehyde with a Variety of 1,3-Dienes Promoted by Et_3B[a]

run	diene	time (h)	products (% yield) [1,3-*anti*/*syn* or 1,2-*anti*/*syn*][b]	
1	**1a**	21	**2.1** (77)	**3.1** (13)
2	**1b**	35	**2.2** (90) [15:1]	
3	**1c**	45	**2.3** (90) [exclusive]	
4	**1d**	48	**2.4** (59) [exclusive]	**4.1** (6)
5	**1e**	43	**2.5** (90) [exclusive]	
6	**1f**	50	**2.6** (55)	**4.2** (23) [5.5:1]
7	**1g**	24	**2.7** (55)	**4.3** (21) [10:1]
8	**1h**	46	**2.8** (82) [exclusive]	
9	**1i** [*Z*:*E* = 1.9:1]	41	8:1 **2.9** (94) [exclusive]	
10	**1i** [*Z*:*E* = 1.9:1][c]	22	3.7:1 **2.9** (79) [exclusive]	
11	**1j** [*Z*:*E* = 7:1]	28	15:1 **2.10** (95) [exclusive]	
12	**1k**	23	**2.11** (86) [exclusive]	
13	**1l**	47	**2.12** (79) [exclusive]	
14	**1m**	29	**2.13** (35) [10:1]	**4.4** (49) [5:1]
15	**1n**	29	**2.14** (12) [exclusive]	**4.5** (58) [exclusive]
16	**1o**	77	**2.15** (57)	**4.6** (23)
17	**1p**	34	No Reaction	
18	**1q**	56	No Reaction	

[a] Reaction conditions: **1** (4 mmol), benzaldehyde (1 mmol), $Ni(acac)_2$ (10 mol %), and Et_3B (240 mol %, 1 M in hexane) in THF (5 mL) at room temperature under N^2. [b] Only major isomers are shown. [c] **1i** (1 mmol) was used instead of 4 mmol.

(11) (a) Kimura, M.; Fujimatsu, H.; Ezoe, A.; Shibata, K.; Shimizu, M.; Matsumoto, S.; Tamaru, Y. *Angew. Chem., Int. Ed.* **1999**, *38*, 397−400. (b) Shibata, K.; Kimura, M.; Shimizu, M.; Tamaru, Y. *Org. Lett.* **2001**, *3*, 2181−2183.

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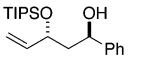
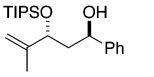
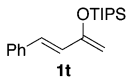
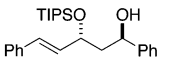
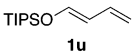
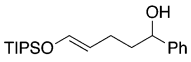
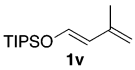
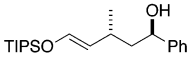
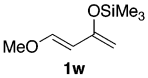
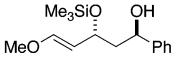
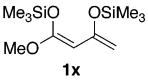
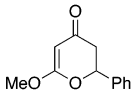
(13) Kimura, M.; Miyachi, A.; Kojima, K.; Tanaka, S.; Tamaru, Y. *J. Am. Chem. Soc.* **2004**, *126*, 14360−14361; Kimura, M.; Miyachi, A.; Kojima, K.; Tanaka, S.; Tamaru, Y. *J. Am. Chem. Soc.* **2005**, *127*, 10117.

Table 2. Ni^0-Catalyzed Homoallylation of Benzaldehyde with Siloxy-1,3-Butadienes Promoted by Et_3B[a,b]

run	diene	time (h)	product (% yield) [1,3-*anti*/1,3-*syn*]
1	 **1r**	68	 **2.16** (65%) [exclusive]
2	 **1s**	35	 **2.17** (84%) [exclusive]
3	 **1t**	46	 **2.18** (81%) [exclusive]
4	 **1u**	43	 **2.19** (92%)
5	 **1v**	43	 **2.20** (92%) [exclusive]
6	 **1w**	24	 **2.21** (69%) [exclusive]
7	 **1x**	10	 **5** (61)

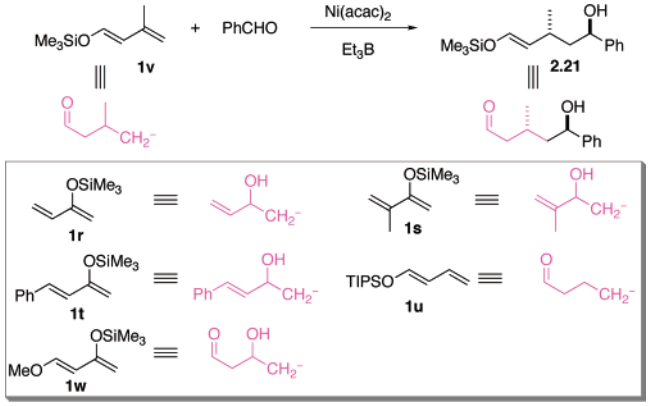
[a] See footnote a, Table 1. [b] TIPS = Si(*i*-Pr)$_3$.

(**2.4** and **4.1**, respectively, run 4). C1 substituents are not so influential to determine the regioselectivity, and both C1-Me butadiene **1f** and C1-Ph butadiene **1g** form mixtures of C4- and C1-adducts in ~2:1 ratio (runs 6 and 7).[14]

The results listed in runs 8−11 are in accord with these substituent effects. For example, both methyl groups of **1h** cooperate to promote the reaction at C4 and provide **2.8** as a single regioisomer in excellent yield. C1- and C2-methyl groups of **1i** are expected to operate oppositely; however, the result indicates that C2-Me is more influential than C1-Me, furnishing a C1-adduct **2.9** exclusively (runs 9 and 10). A triene **1j** is, in principle, capable of reacting at C1, C3, C4, and C6; in fact, however, it reacted selectively at C1 and furnished **2.10** exclusively in excellent yield (run 11). Interestingly, an electron-deficient and electronically strongly biased diene, methyl sorbate (**1l**), reacted with similar ease and furnished a C1-adduct **2.12** in good yield and with excellent regio- and stereoselectivity. The experiments of runs 14 and 15 clearly indicate that the regioselectivity displayed by methyl sorbate stems from electronic factors rather than from other factors such as coordination of an oxygen atom to a nickel species. The formation of **4.6** in a considerable amount for the reaction of **1o** is quite unexpected since, first of all, the product **4.6** is sterically congested and, furthermore, both the C1 substituents are expected to promote C−C formation at a distal diene terminal to give **2.15** selectively (cf., runs 6, 7, and 11). Cyclohexadiene (**1p**) turned out to be unreactive, and no reaction was observed.[8a,c] The low reactivity of **1q** may be attributed to its low coordination ability to a nickel species.

As for the stereoselectivity, in most cases, C2-substituted dienes generally provide 1,3-*anti*-**2** exclusively. The stereoselectivity of C1-substituted dienes depends on the geometry of the starting dienes. (*E*)-Dienes provide 1,2-*anti*-**2** almost exclusively (runs 13−15), and (*Z*)-dienes seem to provide 1,2-*syn*-**2** with high selectivity (runs 9−11). Enrichment of 1,2-*syn*-isomers **2.9** and **2.10** as compared with the *Z* contents of the starting dienes **1i** and **1j**, respectively, may be attributed to the high reactivity of the (*Z*)-isomers as compared with the (*E*)-isomers. In fact, as illustrated in run 10, where 1 equivalent of **1i** was used with respect to benzaldehyde, as opposed to 4 equivalents under usual conditions, the 1,2-*syn*-**2.10**/1,2-*anti*-**2.10** ratio was reduced to 1/2.

Scheme 1. Siloxydienes as the Synthetic Equivalents of Functionalized Butenyl and Butyl Anions; TIPS = Si(*i*-Pr)$_3$



As is apparent from Table 1, homoallylation is a quite general reaction pattern for a wide structural variety of dienes. The parent 1,3-butadiene (**1a**) is only one exception that provides an allylation product **3.1** as a minor product together with a homoallylation product **2.1** as a major product. This exceptional result might be attributed to isomerization of the primary product **2.1** to the thermodynamically more stable isomer **3.1**, as is sometimes observed for transition metal catalysis, especially for nonbranched alkenes.

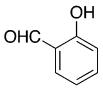
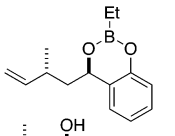
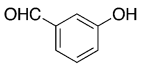
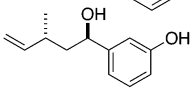
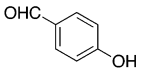
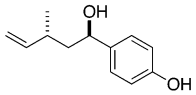
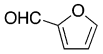
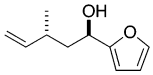
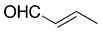
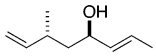
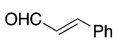
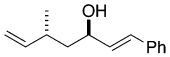
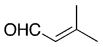
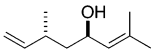
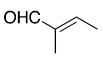
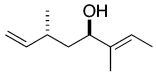
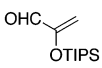
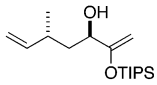
As summarized in Table 2, C1- and C2-siloxydienes react with benzaldehyde highly regio- and stereoselectively and furnish homoallylation products **2.16**−**2.21** as single regio- and stereoisomers in good to excellent yields. A siloxy group surpasses a methyl group in regiocontrolling effect and C2-siloxy directs butadiene to react at C1, and C1-siloxy does at C4 exclusively. For example, **1s** reacted at C1 exclusively, and **1u** provided a C4 addition product **2.19** exclusively.

Tri-alkoxydiene **1x** suddenly turned the reaction course and underwent the hetero Diels−Alder reaction (run 7). The reaction was complete within a short period of time at room temperature and provided a cycloaddition product **5** as a single product.

As illustrated in Scheme 1, the present homoallylation with siloxy- and methoxy-substituted dienes is of great synthetic value. The product **2.21** is easily converted to *anti*-5-phenyl-5-hydroxy-3-methylpentanal; hence, the diene **1v** may be regarded as a synthetic equivalent of a bis-homoenolate of an aldehyde, 3-methylbutanal. The same product may be obtained by the reaction with the corresponding lithium or magnesium reagent with protection of the aldehyde group; in this reaction, however, one can hardly expect such a high 1,3-*anti*-selectivity of **2.21**. Similarly, **1r** may be regarded as a synthetic equivalent of 2-hydroxy-3-butenylmetal species, which is capable of introducing 1,3-*anti* stereoselectivity in the product, **2.16** (run 1, Table 2). In the rectangle in Scheme 1 are shown the examples of synthetic equivalents of other siloxydienes, among which **1w**

(14) Sato, Y.; Sawaki, R.; Saito, N.; Mori, M. *J. Org. Chem.* **2002**, *67*, 656−662.

Table 3. Ni^0-Catalyzed Homoallylation of Aromatic and Unsaturated Aldehydes with Isoprene Promoted by Et_3B[a,b]

run	aldehyde	time (h)	product (% yield) [1,3-*anti*/1,3-*syn*]
1		50	 **2.22** (90) [6:1]
2		48	 **2.23** (96) [10:1]
3		41	 **2.24** (92) [10:1]
4		22	 **2.25** (77) [exclusive]
5		48	 **2.26** (74) [7:1]
6		70	 **2.27** (81) [exclusive]
7		21	 **2.28** (69) [exclusive]
8		16	 **2.29** (60) [exclusive]
9		44	 **2.30** (77) [exclusive]

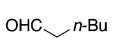
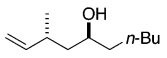
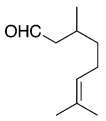
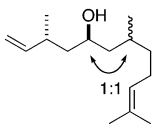
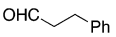
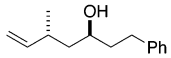
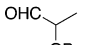
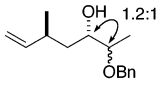
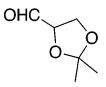
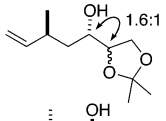
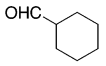
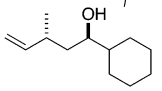
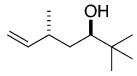
[a] Isoprene (4 mmol), an aldehyde (1 mmol), Ni(acac)$_2$ (10 mol %), and Et_3B (240 mol %, 1 M in hexane) in THF (5 mL) at room temperature under nitrogen. [b] TIPS = Si(*i*-Pr)$_3$.

may be of particular importance in view of the synthesis of polyketide natural products.[15]

In Table 3 are summarized the reactions of isoprene with *o*-, *m*-, *p*-hydroxybenzaldehydes, furfural, and unsaturated aldehydes. As observed in runs 1−3, Et_3B seems to withstand hydrolysis by acidic phenols[16] under the conditions and provides expected products in excellent yields. No extra amounts of Et_3B were applied in these experiments. Salicylaldehyde forms a cyclic boronic acid ester **2.22**, which is stable toward hydrolysis during aqueous workup and can be isolated by means of column chromatography over silica gel. Furfural reacts as usual and provides an expected product **2.25** with excellent stereoselectivity. Unsaturated aldehydes, irrespective of their substitution pattern, undergo homoallylation selectively with very high 1,3-*anti* selectivity (runs 5−9, Table 3). In every case, the geometry of the double bond of the starting aldehydes remains intact.

2. Reaction of Aliphatic Aldehydes with Dienes Promoted with Et_3B. The addition reaction of organometallics of low nucleophilicity upon aliphatic aldehydes sometimes suffers from low yields, not only because of their diminished electrophilic reactivity, as compared with those of aromatic aldehydes but also because of their propensity to undergo enolization and many other side reactions. As is apparent from runs 1−5 in Table 4,

Table 4. Ni^0-Catalyzed Homoallylation of Aliphatic Aldehydes with Isoprene Promoted by Et_3B[a]

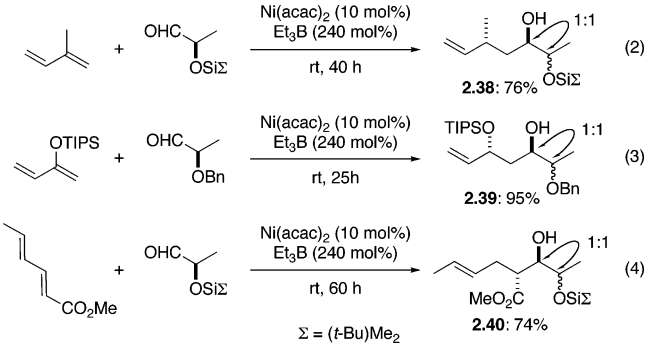
run	aldehyde	time (h)	product (% yield) [1,3-*anti*/1,3-*syn*][b]
1		31	 **2.31** (80) [exclusive]
2		24	 **2.32** (89) [exclusive]
3		24	 **2.33** (48) [exclusive]
4		24	 **2.34** (92) [exclusive]
5		47	 **2.35** (66) [exclusive]
6		24	 **2.36** (28) [exclusive]
7		48	 **2.37** (16) [exclusive]

[a] See footnote a, Table 3. [b] Only major isomers are shown.

isoprene is reactive enough under usual conditions toward primary alkyl aldehydes (runs 1−3) and sterically less-hindered secondary alkyl aldehydes (runs 4 and 5), providing homoallylation products in good yields and with excellent stereoselectivity.

The yields suddenly are lower for the homoallylation of sterically demanding cyclohexanecarbaldehyde and pivalaldehyde (runs 6 and 7). However, even in these cases, the reactions showed high 1,3-*anti*-selectivity. The homoallylation of such aldehydes could be performed successfully with diethylzinc (section 4).

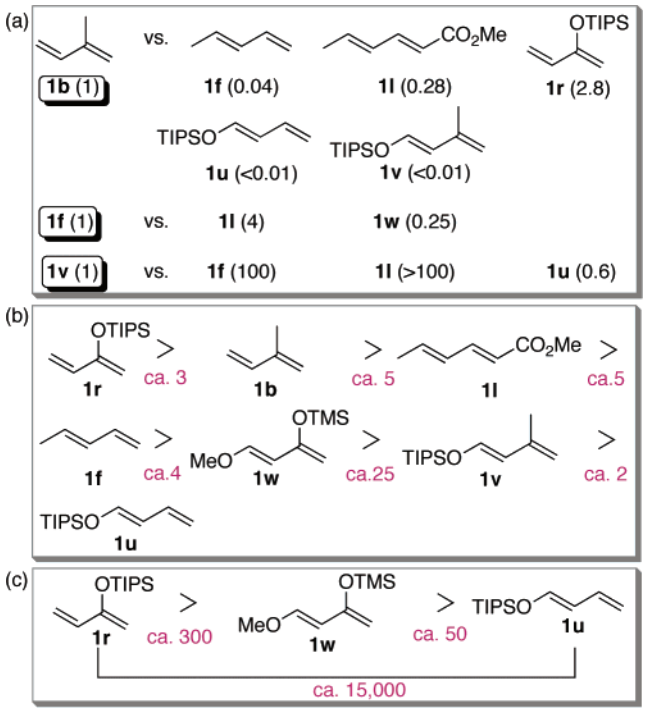
The examples shown in runs 2, 4, and 5 indicate that the present homoallylation with isoprene shows almost no diastereofacial selectivity with respect to the α- and β-stereocenters of aldehydes.[17] Other electron-rich and electron-deficient dienes also showed almost no diastereofacial selectivity (eqs 3 and 4).



3. Relative Reactivity of Dienes. Through experiments, we have realized that 1-siloxy- and 1-methoxybutadiene show apparently lower reactivity than other dienes. In fact, the

(15) (a) Beaudry, C. M.; Trauner, D. *Org. Lett.* **2005**, *7*, 4475−4477. (b) Smith, A. B., III; Walsh, S. P.; Frohn, M.; Duffey, M. O. *Org. Lett.* **2005**, *7*, 139−142. (c) Subba R. G. S. R. *Pure Appl. Chem.* **2003**, *75*, 1443−1451. (d) Shepherd, J. N.; Myles, D. C. *Org. Lett.* **2003**, *57*, 1027−1030.
(16) Pelter, A.; Smith, K.; Brown, H. C. *Borane Reagent*; Academic: London, 1988.
(17) Jurczak, J.; Pikul, S. Bauer, T. *Tetrahedron* **1986**, *42*, 447−488.

Scheme 2. Relative Reactivity of Dienes Determined by Competition Reaction with 1,3-Dienes (2 equiv each) Against Benzaldehyde for the Ni^0-Catalyzed, Et_3B-Promoted Homoallylation; (a) Relative Amounts of Products Isolated; (b) Relative Reactivity; (c) Selected Examples of Relative Reactivity; TIPS = $Si(i\text{-}Pr)_3$; TMS = $SiMe_3$



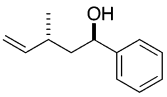
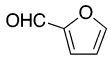
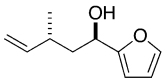
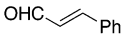
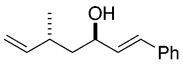
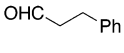
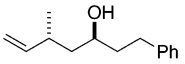
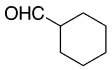
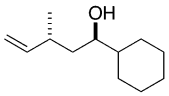
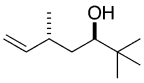
competition experiments that were performed using two kinds of dienes (2 mmol each) and benzaldehyde (1 mmol) in the presence of $Ni(acac)_2$ (10 mol %) and Et_3B (240 mmol) at room temperature revealed that 2-siloxydiene (**1r**) was ~3 times as reactive as isoprene; while, surprisingly, 1-siloxydiene (**1u**) was less reactive more than 100 times than isoprene (Scheme 2a); in the competition reaction between isoprene and **1u**, only an isoprene−benzaldehyde adduct **2.2** was formed in a quantitative yield, and no trace of a **1u**−benzaldehyde adduct **2.19** was detected. In Scheme 2a are summarized the results obtained for the three series of experiments using isoprene (**1b**), 1,3-pentadiene (**1f**), and 3-methyl-1-siloxy-1,3-butadiene (**1v**) as the standards. On the basis of these results, the relative reactivity among dienes is estimated as shown in Scheme 2b.

Interestingly, the relative reactivity seems to have nothing to do with the nucleophilic reactivity (e.g., HOMO) of dienes. For example, electron-deficient methyl sorbate (**1l**) is 5 times as reactive as 1-methyl-1,3-butadiene (**1f**). The most striking is that 2-siloxy-1,3-butadiene (**1r**) is 15 000 times as reactive as 1-siloxy-1,3-butadiene (**1u**) and the former is the most reactive and the latter is the least reactive among 1,3-dienes examined (Scheme 2c). Generally, 1-siloxy group seems to greatly retard the reaction. On the other hand, 2-siloxy group seems to slightly accelerate the reaction.

The conformation of dienes (s-*cis* vs s-*trans*) seems to be another important factor by which to determine their reactivity toward the present homoallylation, since cyclohexadiene, a s-*cis* diene, hardly participates in the reaction (run 17, Table 1). Mechanistic rationale for the unique reactivity of dienes is given in section 6 (Mechanistic Consideration).

4. Homoallylation of Aldehydes and Ketones Promoted with Et_2Zn. Diethylzinc (Et_2Zn), in general, shows higher reactivity than Et_3B. Hence, we tried Et_2Zn in place of Et_3B to promote the homoallylation of particular combinations of aldehydes and dienes that is not successful by making use of Et_3B. We soon realized that Et_2Zn is too reactive to promote selectively the homoallylation of aryl aldehydes and unsaturated aldehydes (runs 1−3, Table 5). Aryl aldehydes were so reactive that they always accompanied the direct reaction with Et_2Zn and formed ethylation products **6** as undesirable side products (footnotes d and e, Table 5).[18] Unsaturated aldehyde was subject to the Michael addition of an ethyl group of Et_2Zn; cinnamaldehyde did not produce the expected product **2.27** at all; instead, 3-phenylpentanal was furnished as the major isolated product (run 3).

Table 5. Ni^0-Catalyzed Homoallylation of Aromatic and Aliphatic Aldehydes with Isoprene Promoted by Et_2Zn[a]

run	aldehyde	time (h)	product (% yield)	[1,3-*anti*/1,3-*syn*][b]
1	OHC−Ph	1[c,d]		**2.2** (71) [15:1]
2		1[c,e]		**2.25** (65) [15:1]
3		0.5[f]		**2.27** (0)
4		1		**2.33** (73) [15:1]
5		0.5		**2.36** (83) [30:1]
6		1		**2.37** (66) [20:1]

[a] Isoprene (4 mmol), an aldehyde (1 mmol), $Ni(acac)_2$ (10 mol %), and Et_2Zn (240 mol %, 1 M in hexane) in THF (5 mL) at room temperature under nitrogen. [b] Only major isomers are shown. [c] At 0 °C. [d] 1-Phenylpropan-1-ol (**6.1**: 16%). [e] 1-(2-Furyl)propan-1-ol (**6.2**: 3%). [f] 3-Phenylpentanal (28%).

For the less reactive aliphatic aldehydes, Et_2Zn turned out to be the choice of reagents, and the expected homoallylation products were obtained in greatly improved yields (runs 4−6, Table 5, vs runs 3, 6, and 7, Table 4). In these small-scale experiments, no direct ethylation was observed; however, for large-scale experiments, the ethylation sometimes becomes a serious side reaction (section 5)

Under the Et_3B−Ni catalysis, no productive results were obtained for the reaction with ketones. In sharp contrast, as exemplified in Scheme 3 and Table 6, the Et_2Zn−Ni catalysis nicely promoted the homoallylation of ketones. However, we met for the first time small erosion in regioselectivity in these reactions (eqs 5 and 6); isoprene reacted with acetone, cyclohexanone, and protected dihydroxyacetone[19] both at C1 and C4 positions and provided mixtures of homoallylation products **2** and **4** in a ratio of ~5−6:1.

As observed for chiral aldehydes (Table 4), the diastereofacial selectivity for ketones was also modest; irrespective of the steric

(18) Hirano, K.; Yorimitsu, H.; Oshima, K. *Org. Lett.* **2005**, *7*, 4689−4691.
(19) González-García, E. M.; Grognux, J.; Wahler, D.; Reymond, J.-L. *Helv. Chim. Acta* **2003**, *86*, 2458−2470.

Scheme 3. Ni^0-Catalyzed Homoallylation of Ketones with Isoprene or 2,3-Dimethyl-1,3-butadiene Promoted by Et_2Zn: Steric Effects of Ketone on Regio- and Stereoselectivity

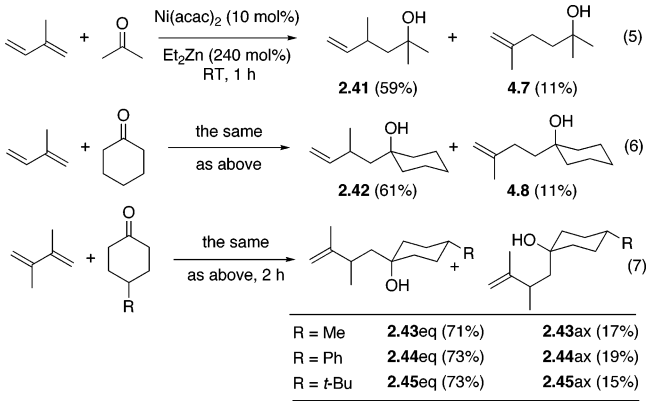
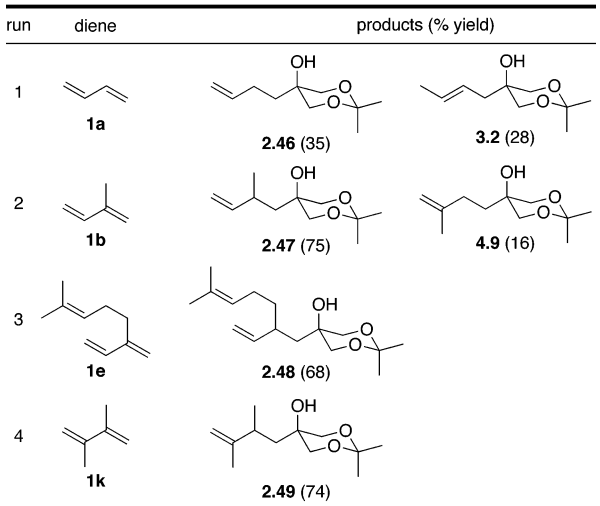
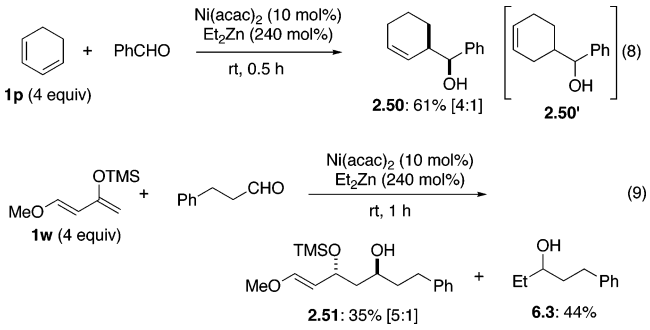


Table 6. Ni^0-Catalyzed Homoallylation of Protected Dihydroxyacetone with 1,3-Dienes Promoted by Et_2Zn[a]



[a] Reaction conditions: **1** (4 mmol), 2,2-dimethyl-1,3-dioxacyclohexan-5-one (1 mmol),[19] Ni(acac)$_2$ (10 mol %), and Et_2Zn (240 mol %, 1 M in hexane) in THF (5 mL) at room temperature for 2 h under N^2.

Scheme 4. Reactions of Unreactive Dienes: Homoallylation with Electron-Rich Diene **1w** and Allylation with Cyclohexadiene (**1p**), Both Being Effected Only with Et_2Zn, but Not with Et_3B



size of the C4 substituents of 4-substituted cyclohexanones, ~4−5:1 mixtures of the equatorial/axial approach products resulted (eq 7, Scheme 3).

The reactions shown in Scheme 4 clearly demonstrate the utility of Et_2Zn as a promoter. As mentioned before (run 17, Table 1), cyclohexadiene failed to react with benzaldehyde under the Et_3B−Ni catalysis; however, the catalytic system Et_2Zn−Ni did promote the reaction (eq 8).[20] The reaction proceeded smoothly at room temperature and was complete within 30 min. According to the results reported by Loh,[21] we have long regarded the product structure as **4.50′**. However, the major isomer of **2.50** showed the ^{13}C NMR (100 MHz) and ^1H NMR (400 MHz) spectra completely superimposable to those of the product, *syn*-1-(2-cyclohexenyl)-1-phenylmethanol, obtained exclusively by the allylation of benzaldehyde with 2-cyclohexenyl benzoate through umpolung reaction catalyzed by palladium.[22] The structure of **2.50** was further determined unequivocally by a chemical transformation technique (eq h, Scheme 9). This indicates that cyclohexadiene is unique both in its reactivity and regioselectivity among dienes and selectively undergoes *allylation*, not *homoallyl*ation.[13]

Table 7. Ni^0-Catalyzed, Et_3B-Promoted Homoallylation of Benzaldehyde with Dienes with Reduced Amounts of Ni(acac)$_2$ and Dienes[a]

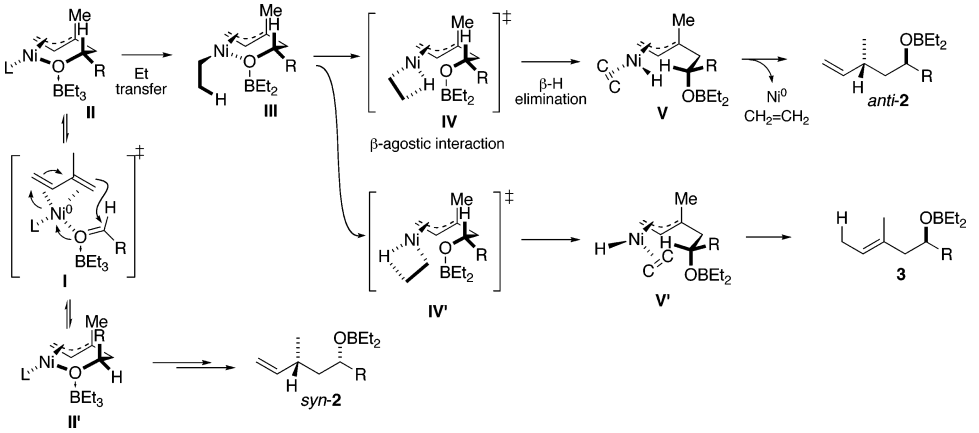
run	diene (mol %)	Ni(acac)$_2$ (mol %)	Et_3B (mol %)	scale[b] (mmol)	time (h)	product **2** (% isolated yield)
1	**1b** (400)	10.0	240	1	35	**2.2** (90)
2	**1b** (400)	2.5	240	2	35	**2.2** (94)
3	**1b** (400)	1.0	240	5	48	**2.2** (82)
4	**1b** (200)	1.4	200	50	24	**2.2** (93)
5	**1*l*** (400)	10.0	240	1	47	**2.12** (79)
6	**1*l*** (400)	1.0	240	5	66	**2.12** (91)
7	**1r** (400)	10.0	240	1	68	**2.16** (65)
8	**1r** (200)	5.0	240	1	65	**2.16** (65)
9	**1r** (110)	5.0	240	2	65	**2.16** (62)

[a] A mixture of a diene (indicated amount), benzaldehyde (1 mmol), Ni(acac)$_2$ (indicated amount), and Et_3B (indicated amount) at room temperature under N^2. [b] The scale of reaction based on the amount of benzaldehyde.

5. Optimization of Reaction Conditions For Practical Use: Reduced Loading of Ni(acac)$_2$ and Dienes and Application to Multigram-Scale Experiments. To compare the reactivity and selectivity of dienes and aldehydes, the reactions discussed so far have been undertaken uniformly under the conditions using Ni(acac)$_2$ (10 mol %), a diene (400 mol %), an aldehyde or ketone (1 mmol), and Et_3B (240 mol %) or Et_2Zn (240 mol %). The conditions are not satisfactory for practical use with respect to the turnover numbers of the catalyst, diene loadings, and the scales of experiments. Accordingly, we next tested the reaction with reduced loadings of the catalysts and dienes in large-scale experiments. In Table 7 are summarized the results. The homoallylation of benzaldehyde with isoprene (**1b**) is summarized in runs 1−4, which clearly indicate that Ni(acac)$_2$ loading can be reduced to 1 mol % without significant

(20) Ni-Catalyzed intramolecular reductive cyclization of cyclohexadienyl aldehydes provides mixtures of allylation and homoallylation products: Yeh, M.-C. P.; Liang, J.-H.; Jiang, Y.-L.; Tsai, M.-S. *Tetrahedron* **2003**, *59*, 3409−3415.
(21) Loh, T.-P.; Song, H.-Y.; Zhou, Y. *Org. Lett.* **2002**, *4*, 2715−2717.
(22) Tamaru, Y.; Tanaka, A.; Yasui, K.; Goto, S.; Tanaka, S. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 787−789.

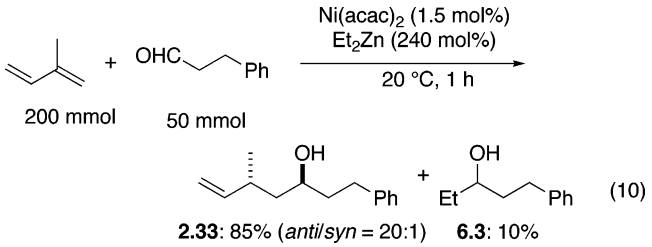
Scheme 5. Plausible Reaction Pathway Selectively Leading to 1,3-*anti*-**2**



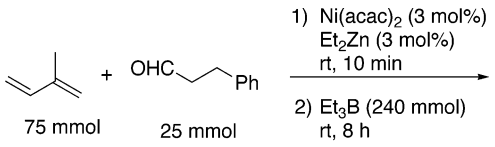
decrease in the yields. Especially rewarding are the results in run 4 that has been undertaken with a 50 mmol scale of benzaldehyde and 2 equiv of Et_3B; the product **2.2** was obtained in 93% isolated yield (1,3-*anti*/1,3-*syn* = 30:1, 8.09 g) by a single Kugelrohr distillation of the reaction mixture after an appropriate aqueous workup. Methyl sorbate (**1l**) also reacts with benzaldehyde using reduced amount of $Ni(acac)_2$ in a 5 mmol scale experiment (run 6).

Reduced diene loadings may be a strong concern when dienes are expensive and/or require multisteps for the preparation. The results in runs 7−9 indicate that 2-siloxy-1,3-diene (**1r**) loading could be reduced to 1.1 equiv to an aldehyde without significant loss in the yield.

In eq 10 is shown a 10 g-scale reaction of isoprene and dihydrocinnamaldehyde using reduced loading of $Ni(acac)_2$, where **2.33** was obtained in 85% yield (8.67 g, *anti/syn* = 20:1) together with a ethylation product **6.3** (10%). In this large-scale experiment, both the yield and diastereoselectivity are significantly improved as compared with those under the usual 1 mmol-scale reaction conditions (run 4, Table 5); however, the ethylation became a serious side reaction. The ethylation seems to be subject of the steric size of aldehydes, and under the identical reaction conditions sterically hindered cyclohexanecarboxaldehyde (50 mmol) provided **2.36** in 93% yield (8.46 g, *anti* exclusive, not shown) together with a reduced amount of the ethylation product, 1-cyclohexyl-1-ethylmethanol (**6.4**) in 5% yield.



After many experimentations in pursuit of suppressing the ethylation in large-scale experiments, we have finally reached a satisfactory procedure: a pretreatment of $Ni(acac)_2$ (3 mol %) with one equivalent of Et_2Zn (3 mol %) at ambient temperature, followed by addition of Et_3B (240 mol %), an aldehyde, and isoprene (300 mol %) at ambient temperature (eq 11).[23] According to this procedure, dihydrocinnamaldehyde (25 mmol) and cyclohexanecarboxaldehyde (25 mmol) provided the homoallylation products **2.33** (80%, *anti/syn* = 30:1) and **2.36** (85%, *anti* exclusive, not shown), respectively, both not being contaminated with the corresponding ethylation products. Taking the results of runs 3 and 6 in Table 4 into consideration, these results suggest that a catalytic amount of Zn(II) species plays a pivotal role in acceleration of the homoallylation with Et_3B.

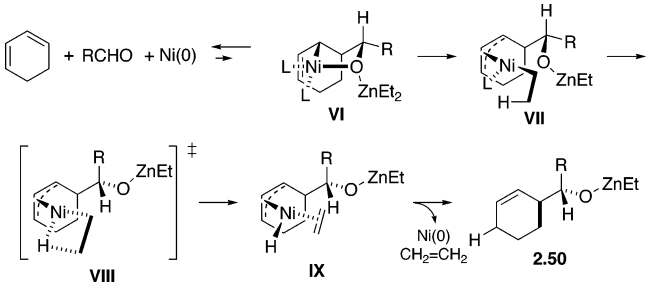


6. Mechanistic Consideration. In Scheme 5 is proposed the most plausible reaction pathway that accommodates all reaction features characteristic of the present homoallylation reaction: e.g., stereoselectivity leading to *anti*-**2** selectively over *syn*-**2** and regioselectivity leading to the homoallylation products **2** selectively over the allylation products **3**, using isoprene as a representative of dienes.

The regioselectivity of dienes (reacting either at C1 or C4 with an aldehyde) might be mainly under the control of the electron densities on the diene termini, and the terminal bearing the highest electron density would enter into the reaction with an aldehyde. A transition state **I** might lead to an intermediate **II** and/or **II′** through oxidative cyclization of a Ni(0) species across isoprene and an aldehyde. The oxidative cyclization might be accelerated by coordination of Et_3B (or Et_2Zn) to an aldehyde.[24,25] In this process, as illustrated by curved arrows, dienes might serve not only as an electron-push toward aldehydes but also as an electron-pull from a nickel(0) species (electron donation from Ni(0)). For electron-rich dienes the former factor might be important, and for electron-deficient dienes the latter factor might be crucial. Thanks to these two mechanisms, many kinds of electron-rich and electron-deficient dienes might be able to engage in the present homoallylation.

(23) Tamaru, Y.; Kimura, M. *Org. Synth.* **2006**, *83*, 88−96.
(24) Ogoshi, S.; Oka, M.; Kurosawa, H. *J. Am. Chem. Soc.* **2004**, *126*, 11802−11803.
(25) Ogoshi, S.; Ueta, M.; Arai, T.; Kurosawa, H. *J. Am. Chem. Soc.* **2005**, *127*, 12810−12811.

Scheme 6. A Rationale for Allylation (not Homoallylation) with Cyclohexadiene

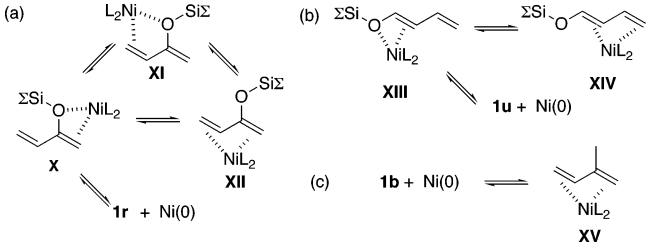


Intermediates **II** and **II′** are diastereomeric to each other. Since the latter suffers from 1,3-diaxial repulsion between an aldehyde R and isoprene Me, the reaction might proceed selectively through **II**. Ethyl transfer from B to Ni, accompanied by an ionic Ni−O bond cleavage, would form an intermediate **III**, which might undergo β-H elimination in two ways. The route leading to **V** is expected to be much favored over the one leading to **V′**, since β-agostic interaction of the Et group with the vacant site on Ni, *cis* to the Et group, created by dissociation of an oxygen ligand, would readily take place (a transition state **IV**). On the other hand, the route leading to **V′** requires geometrical change around Ni from *trans* to *cis* with respect to the ethyl and alkoxy groups before β-H elimination takes place, hence, having to pass through barrier(s) high in energy.[26] Reductive elimination of Ni(0) from **V** might provide a homoallylation product, *anti*-**2**, whereas the same process via **V′** might result in the formation of an allylation product, **3**.

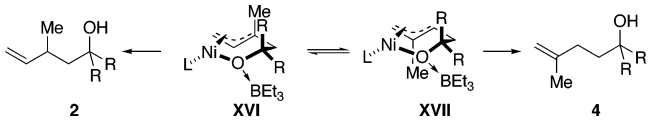
The cyclic oxa-π-allylnickel structures **II** and **II′** are geometrically possible only for s-*trans* dienes, and cyclohexadiene, a s-*cis* diene, might be obliged to form a less stable cyclic oxa-σ-allylnickel complex **VI** (Scheme 6). The two factors, (1) formation of **VI** through activation of an aldehyde by the coordination with strongly Lewis acidic and sterically small Et_2-Zn, and not Et_3B, and (2) a facile Ni−O bond cleavage and ethyl group transfer from Zn to Ni, forming a π-allyl(ethyl)-nickel(II) intermediate **VII** would be essential to put the reaction forward; otherwise, **VI** might be fragmented into the starting materials through which cyclohexadiene would be able to restore its conjugate stabilization. The crucial role of Lewis acids to promote the oxidative cyclization of $Ni(cod)_2$ upon olefinic aldehydes and ketones (e.g., *o*-allylbenzaldehyde[24] and *o*-allylacetophenone)[25] has been demonstrated by Ogoshi and Kurosawa. The π-allyl(ethyl)nickel(II) intermediate **VII**, being *cis* with respect to ethyl and alkoxy groups, might undergo β-H elimination via a transition state **VIII** and provide an intermediate **IX**, which might be destined to undergo reductive elimination to provide an allylation product **2.50** (eq 8).

As mentioned before (Scheme 2), 1-siloxy and 2-siloxy groups exert a contrasting effect on the reactivity of dienes; the former greatly diminishes the reactivity of dienes toward the homoallylation of aldehydes, whereas the latter slightly increases the reactivity. A rationale for this unique behavior of siloxy group is given in Scheme 7, where it is supposed that both vinyl ethers and allyl ethers coordinate to Ni(0) more strongly than dienes do (e.g., [**X**], [**XI**] > [**XII**]). Accordingly, the concentration of a reactive Ni(0)/diene complex **XII** should be much smaller than those of η^2,η^2-nickel complexes of usual dienes under comparable conditions (e.g., [**XV**], Scheme 7c). However, the high nucleophilicity of **XII**, bestowed by electron donation of the siloxy group, might well compensate for its low concentration, resulting in the relative reactivity of **1r**/**1b** = ∼3. Here, we expect that complexes **X**−**XII** readily isomerize to one another, just swinging ∼60° around η^2-olefin/nickel bonds. In the case of 1-siloxy dienes, e.g., **1u**, on the other hand, a vinyl ether/nickel complex **XIII** is hardly expected to isomerize to **XIV**, since this process requires 180° rotation around the η^2-olefin/nickel bond (inversion of configuration on the Ni center) and must be associated with barriers high in energy. As a consequence, despite the greatest reactivity (the highest HOMO) among dienes examined, **1u** is least reactive in the present Ni-catalyzed homoallylation reaction.

Scheme 7. Stronger Coordination of Vinyl Ether and Allyl Ether (Σ^2,Σ^2) than Diene (Σ^2,Σ^2) to Ni^0; $\Sigma = Me_3$ or $(i\text{-}Pr)_3$



Scheme 8. A Rationale for Erosion of Regioselectivity (Giving **4** as a Minor Product) in Homoallylation of Ketones



Unlike excellent levels of diastereofacial selectivity that organolithium and -magnesium reagents frequently display for the addition reactions to chiral α-alkoxyaldehydes,[27] the present homoallylation shows almost no diastereofacial selectivity (eqs 2−4 and runs 4 and 5, Table 4), suggesting no chelate formation either in a transition state **I** or in an intermediate **II** (or **II′**). In fact, as apparently seen in **II** (or **II′**), its cyclic structure and square-planar geometry of Ni(II) prohibit the oxygen of R = $CH(R')OSiR''_3$ from coordination to Ni(II).

The erosion of regioselectivity with respect to the reaction site of isoprene observed for the homoallylation of ketones (eqs 5 and 6 in Scheme 3 and run 2 in Table 6) might be due to 1,3-diaxial repulsion between isoprene Me and ketone R in an intermediate **XVI** that is inevitable for the reaction with ketones (Scheme 8). In such cases, an intermediate **XVII** would be formed at the expense of favorable electronic effects in forming **XVI**.

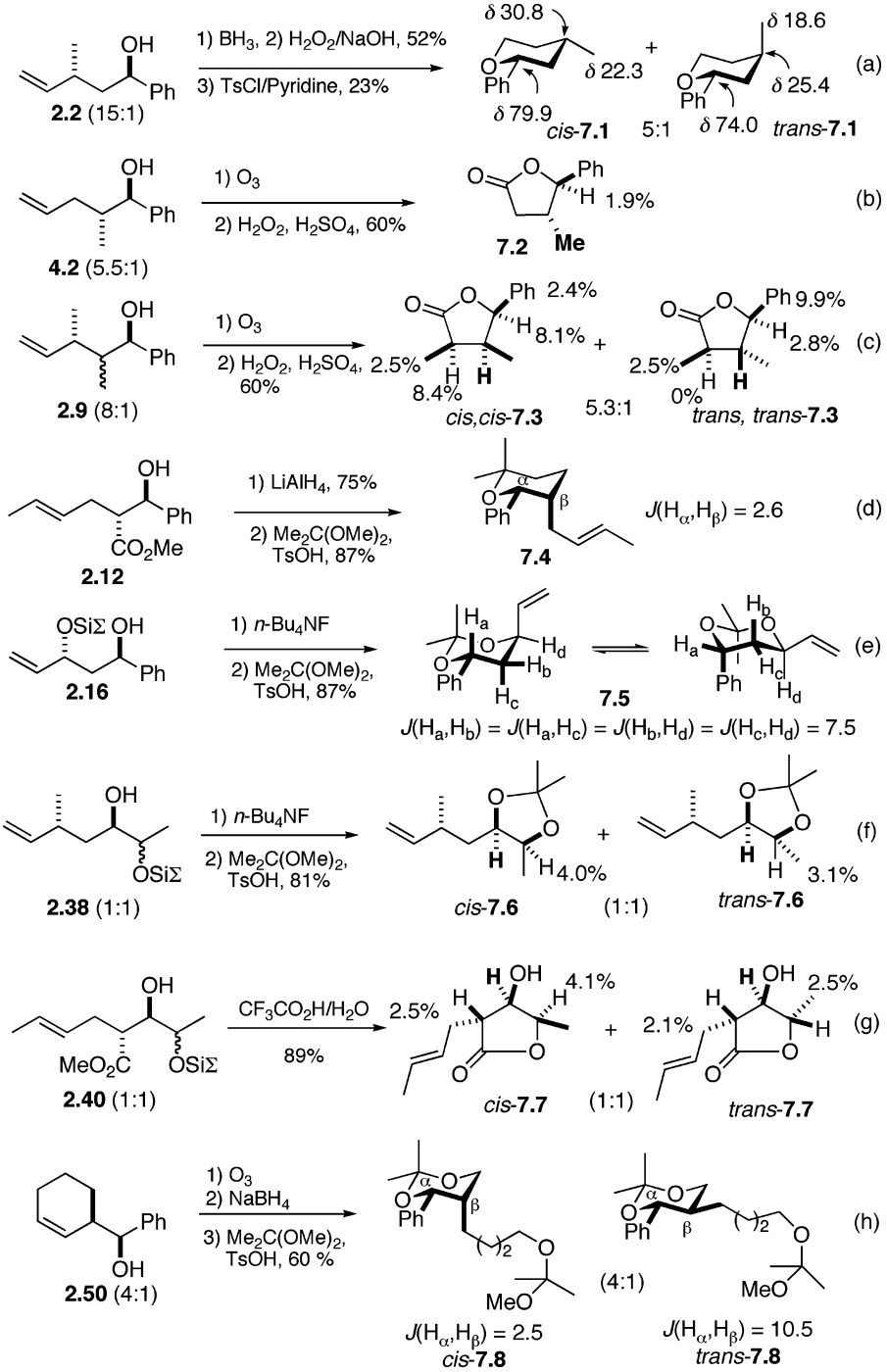
The reversible formation of oxa-π-allylnickel acycle complexes between like **II** and **II′** (Scheme 5) and **XVI** and **XVII** (Scheme 8) was verified by Ogoshi and Kurosawa.[28] They have succeeded in the isolation and the X-ray structure determination of these complexes and also 2-oxa-nickelacyclopentanes such as **VI** with a monodentate phosphane as a ligand.[24,25]

(26) Espinet, P.; Albéniz, A. C. In *Fundamentals of Molecular Catalysis*; Kurosawa, H.; Yamamoto, A., Eds.; Elsevier Science B. V.: Amsterdam, 2003; Chapter 6.

(27) Eliel, E. L.; Wilen, S. H. *Stereochemistry of Organic Compounds*; John Wiley & Sons: New York, 1994; Chapter 12.

(28) Ogoshi, S.; Tonomori, K.; Oka, M.; Kurosawa, H. *J. Am. Chem. Soc*. **2006**. Published online May 5, 2006, http://dx.doi.org/10.1021/ja060580l.

Scheme 9. Structure Determination[a] of **2**



[a] Figures are chemical shifts δ in ppm for ^{13}C NMR (100 MHz), coupling constants J in Hz for ^{1}H NMR (400 MHz), and % increments of area intensities for NOE (the boldface atoms being irradiated).

7. Structure Determination of Products. The structures of products were determined unequivocally by converting them to cyclic five- and/or six-membered oxygen heterocycles by using standard transformations. The reaction procedures and the diagnostic ^{1}H and ^{13}C NMR data are summarized in Scheme 9.

For example, the structure of **2.9** with 1,2-*syn*-1,3-*anti* and 1,2-*anti*-1,3-*anti* in a ratio of 8:1 was confirmed by the formation of *cis,cis*-lactone **7.3** as a major product together with *trans,-trans*-lactone **7.3** as a minor product (eq c, Scheme 9). The relative configuration of substituents was determined on the basis of the increments of area intensities by irradiations at the β-protons (boldface). The perfect 1,3-*anti* stereochemistry and 1,2-*syn*/1,2-*anti* stereoisomerism in a ratio of 1:1 of **2.38** were confirmed similarly by the transformation to a 1:1 mixture of *cis*- and *trans*-acetonides **7.6** (eq f, Scheme 9).

All the ^{3}J values of **7.5** were identical by chance, probably owing to a rapid equilibrium between the two conformers (eq e) as a consequence of similar 1,3-diaxial repulsions in the left (between one of the acetonide Me groups and vinyl group) and in the right conformer (between the other acetonide Me and Ph) (eq e, Scheme 9).

Discrimination of the two structures **2.50** and **2.50′** (Scheme 4) was achieved by ozonolysis and reduction with $NaBH_4$, followed by acetonization (eq h, Scheme 9). Only two isomers, *cis*- and *trans*-**7.8** with a 1,3-dioxacyclohexane skeleton were obtained in a reasonable overall yield, instead of six isomers as expected from **2.46′**: two with a 1,3-dioxacycloheptane skeleton, two with a 1,3-dioxacyclooctane skeleton, and two with a 1,3-dioxacyclononane skeleton.

Conclusions

$Ni(acac)_2$ catalytically promotes the homoallylation of aldehydes and ketones with 1,3-dienes in the presence of triethylborane or diethylzinc. These organometallics serves as a reducing agent delivering a formal hydride to the C2 position of 1,3-dienes and hence generating a formal homoallyl anion species and enabling the novel homoallylation of aldehydes and ketones. The reaction proceeds smoothly at room temperature in the absence of any phosphane or nitrogen ligands and is highly regioselective and stereoselective for a variety of aldehydes and 1,3-dienes. Unsymmetrical dienes react at the termini with the highest electron density. (*E*)- and (*Z*)-1-substituted dienes selectively provide 1,2-*anti*- and 1,2-*syn*-4-penten-1-ols, respectively, and 2-substituted dienes furnish 1,3-*anti*-4-penten-1-ols with high stereoselectivity. With triethylborane, sterically congested aliphatic aldehydes and ketones fail to react. In such cases, diethylzinc serves as a substitute for triethylborane and yields the expected products in good yields with similarly high regio- and stereoselectivity. 1,3-Cyclohexadiene is one exception among 24 kinds of dienes examined, and undergoes allylation (not homoallylation) selectively only by the Et_2Zn-Ni catalysis. Under the Et_3B-Ni catalysis, the relative reactivity of dienes is as follows: 2-siloxy-1,3-butadiene > isoprene > methyl sorbate > 1,3-pentadiene > 1-siloxy-1,3-butadine. 2-Siloxy-1,3-butadiene is almost 15 000 times as reactive as 1-siloxy-1,3-butadine. Mechanistic rationale is given for the salient reaction features associated with the reaction: (1) regioselectivity of the reaction site of unsymmetrical dienes (C1 vs C4), (2) 1,3-*anti*- selectivity for 2-substituted dienes and 1,2-*syn* and 1,2-*anti*- selectivity for (*Z*)- and (*E*)-1-substituted dienes, respectively, (3) homoallylation (vs allylation) with 1,3-dienes, (4) high reactivity of 2-siloxydienes and very low reactivity of 1-siloxydienes, (5) allylation (not homoallylation) with cyclohexadiene.

Acknowledgment. Financial support from the Ministry of Education, Culture, Sports, Science and Technology, Japanese Government (Grant-in-Aid for Scientific Research (B) 16350058 and Priority Areas 17035065) is gratefully acknowledged.

Supporting Information Available: Experimental section including analytical data and ^1H NMR spectra of all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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