A Grignard-Type Addition of Allyl Unit to Aldehydes by Using Bismuth and Bismuth Salt

Makoto WADA,* Hidenori OHKI,†,†† and Kin-ya AKIBA†
College of General Education, University of Tokushima, Minami-josanjima, Tokushima 770
†Department of Chemistry, Faculty of Science, Hiroshima University, Higashisenda-machi, Hiroshima 730

(Received January 25, 1990)

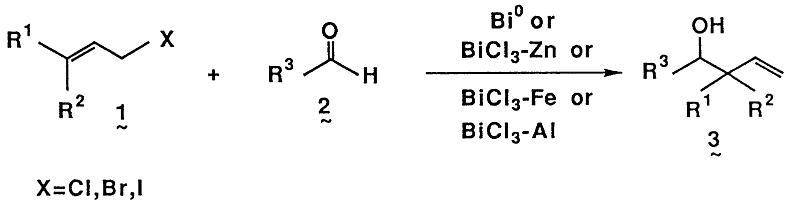
In the presence of metallic bismuth, bismuth(III) chloride-metallic zinc, or bismuth(III) chloride-metallic iron, allylic halides have been found to react with aldehydes under mild conditions to give the corresponding homoallylic alcohols in high yields with high chemo-, regio-, and stereoselectivity. Allylic halides have been also found to react with aldehydes at room temperature in tetrahydrofuran-water by using bismuth(III) chloride-metallic aluminium to afford the expected homoallylic alcohols in high yields.

The addition of allylic organometallics to carbonyl compounds is an important synthetic reaction for the preparation of homoallylic alcohols,[1] and a classical method is the addition of an allylic Grignard reagent which must be prepared cautiously to avoid an undesired coupling reaction, Wurtz-type reaction.[2] Recently, the Grignard-type carbonyl addition of allylic halides has been developed utilizing organometallics derived from a number of metallic elements such as manganese,[3] zinc,[4] tin,[4c,5] antimony,[6] and cerium,[7] where Wurtz-type coupling reaction did not take place.

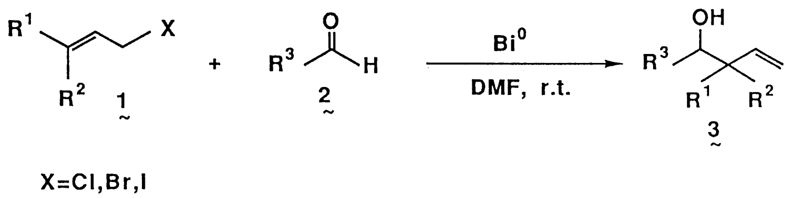
In view of elemental resources for the future, it is important to use various elements for organic synthesis. Among group 5B elements, bismuth metal is cheaper and less toxic than arsenic or antimony and can be expected to play some role in organic synthesis according to its enhanced metallic character. To our knowledge, however, organic synthesis, especially carbon-carbon bond forming reaction using bismuth and bismuth compounds has been scarcely studied.[8] Concerning the Grignard-type carbonyl addition of allylic halides utilizing a metallic element, we had an interest in bismuth. We now wish to disclose in full the first example of carbon-carbon bond forming reaction with elemental bismuth, i,e., metallic bismuth-[Bi(0)], bismuth(III) chloride($BiCl_3$)-metallic zinc[Zn(0)], $BiCl_3$-metallic iron[Fe(0)], and $BiCl_3$-metallic aluminum[Al(0)]-mediated allylation of aldehydes with allylic halides to afford the corresponding homoallylic alcohols in good yields.[9]

Results and Discussion

Metallic Bismuth Mediated Allylation of Aldehydes to Provide Homoallylic Alcohols. The reaction was carried out by the following two procedures. 1) Method A, an allylic halide was treated with Bi(0) in *N,N*-dimethylformamide (DMF) at room temperature (Step I) and then the mixture was reacted with an aldehyde (Step II); 2) Method B, a mixture of an allylic halide and an aldehyde was treated with Bi(0) in DMF at room temperature (Barbier-type reaction). In our



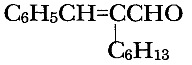
Scheme 1.



Scheme 2.

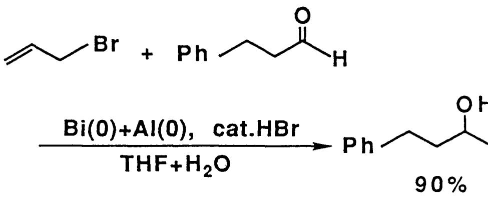
[††] Present address: New Drug Research Laboratories, Fujisawa Pharmaceutical Co., Ltd., 2-1-6, Kashima, Yodogawaku, Osaka 532.

Table 1. Bismuth Mediated Synthesis of Homoallylic Alcohols

Run	Allylic halide	Aldehyde	Ratio[a]	Method	Conditions(r.t.) Step I	Conditions(r.t.) Step II	Yield of **3**(%)[b]
1	$CH_2{=}CHCH_2Br$	C_6H_5CHO	1.1	A	1 h	4 h	89
2	$CH_2{=}CHCH_2Br$	C_6H_5CHO	1.1	A	4 h	2 h	94
3	$CH_2{=}CHCH_2Br$	C_6H_5CHO	1.2	B	5 h		40
4	$CH_2{=}CHCH_2Br$	C_6H_5CHO	1.2	B	12 h		98
5	$CH_2{=}CHCH_2I$	C_6H_5CHO	1.2	B	12 h		98
6	$CH_2{=}CHCH_2Br$	*p*-$MeOC_6H_4CHO$	1.2	A	4 h	2 h	76
7	$CH_2{=}CHCH_2Br$	*p*-$MeOC_6H_4CHO$	1.2	A	2 h	12 h	98
8	$CH_2{=}CHCH_2Br$	$C_6H_5CH_2CH_2CHO$	1.2	A	4 h	2 h	97
9	$CH_2{=}CHCH_2Br$	$C_6H_5CH_2CH_2CHO$	1.2	B	12 h		53
10	$CH_2{=}CHCH_2Br$	$CH_3(CH_2)_7CHO$	1.2	A	4 h	2 h	80[c](85)[d]
11	$CH_2{=}CHCH_2Br$	$CH_3(CH_2)_7CHO$	1.2	B	12 h		58[c]
12	$CH_2{=}CHCH_2Br$	$(CH_3)_2CHCHO$	1.2	A	4 h	3 h	70[e](88)[d]
13	$CH_2{=}CHCH_2Br$	 $C_6H_5CH{=}C(C_6H_{13})CHO$	1.2	A	4 h	3 h	70[f]
14	$CH_2{=}CHCH_2Cl$	C_6H_5CHO	1.1	A	4 h	2 h	0
15	$CH_2{=}CHCH_2Cl$	C_6H_5CHO	1.2	B	28 h		62[g]
16	$CH_2{=}CHCH_2Cl$	C_6H_5CHO	1.2	B	27 h		80[h]
17	$(CH_3)_2C{=}CHCH_2Br$	C_6H_5CHO	1.2	A	3 h	17 h	27[i]

a) The molar ratio of an allylic halide to an aldehyde. The ratio, bismuth/allylic halide, was always 1.0. b) Isolated yields by thin-layer chromatography (hexane : ethyl acetate=9 : 1), based on aldehydes, are given unless otherwise stated. c) Isolated yield by Kugelrohr distillation. d) Estimated by ^{1}H NMR. e) Isolated yield by flash column chromatography (hexane : ethyl acetate=9 : 1). f) 1,2-Addition product was obtained. g) Tetraethylammonium bromide was added to the reaction mixture. h) Sodium iodide was added to the reaction mixture. i) γ-Addition product is a sole product.

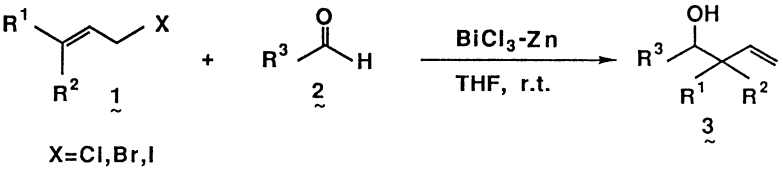
early investigation, commercially available bismuth shot (99.999%, Wako Pure Chemical Industries, Ltd.) was scraped with a rasp for use in the present reaction. Bismuth powder (100 mesh, 99.999%, Aldrich Chemical Co.) was also effective and more convenient for the reaction. Some typical results are described in Table 1. Allyl chloride did not give the expected adduct (**3**) at all (run 14), different from its bromide and iodide. However, the product was obtained by Method B in the presence of tetraethylammonium bromide or sodium iodide (runs 15 and 16). The benzaldehyde/prenyl bromide reaction gave a low yield (run 17), with the more substituted γ-carbon of the allyl group regioselectively attacking the carbonyl carbon. The low yield was improved by Method D (vide infra). Both aromatic and aliphatic aldehydes reacted smoothly to afford the corresponding homoallylic alcohols in good yields (runs 2, 4, 5, 7, 8, 10, and 12). When an α,β-unsaturated aldehyde was used, the 1,2-addition product was obtained selectively (run 13). When tetrahydrofuran (THF) was used as a solvent, the yields of **3** decreased and were not reproducible. A recent paper reports the allylation of aldehydes and ketones with various allylic bromides by using a mixture of metallic aluminium and metallic tin in a two phase system consisting of diethyl ether (Et_2O) and aqueous hydrobromic acid.[5b] Therefore, we tried the reaction of allyl bromide and 3-phenylpropionaldehyde in THF and H_2O at room temperature utilizing Bi(0) and Al(0) in the presence of a catalytic amount of hydrobromic acid to give the corresponding homoallylic alcohol in 90% yield (Eq. 1).



(1)

This reaction did not take place at all in the absence of Bi(0) and was sluggish when Al(0) was not used, and the yield decreased in 47% when H_2O was not added. Hardly any expected product was obtained without a catalytic amount of hydrobromic acid. Such a reaction in aqueous solvent is of interest because organometallic compounds usually have to be prepared and treated in anhydrous solvents owing to rapid protonolysis (vide infra).

$BiCl_3$-Zn(0) Mediated Allylation of Aldehydes to Provide Homoallylic Alcohols. Though effective for the Grignard-type allylation, the Bi(0) mediated allylation reaction was sometimes troublesome in THF as described above. Consequently we searched for another procedure and found that $BiCl_3$-Zn(0) in THF can be utilized in the title reaction (Method C).[10] The overall scheme is shown below. The reaction was carried out as follows. $BiCl_3$ was treated with Zn(0) in THF at room temperature for 1 h and then the resulting black suspension was reacted with a mixture of an allylic halide and an aldehyde for 2 h. Typical



Scheme 3.

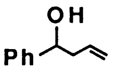
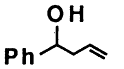
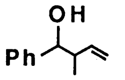
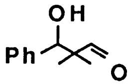
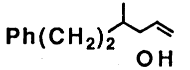
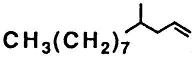
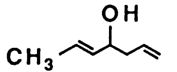
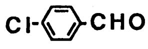
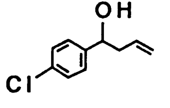
results are summarized in Table 2. Both aromatic and aliphatic aldehydes reacted smoothly to afford the corresponding homoallylic alcohols in good yields. When an α,β-unsaturated aldehyde was used, the 1,2-addition product was obtained selectively. When acetophenone was used, the desired product was obtained in 56% yield, while it was obtained in low yield by Method A and it was not obtained in any significant amount by Method D (vide infra). It is thought that $ZnCl_2$ generated in situ presumably promoted the addition of an allyl group to acetophenone. Based on this reactivity difference between aldehydes and ketones, we could discriminate benzaldehyde from acetophenone (vide infra). In the discrimination reaction, when Zn(0) itself was used under otherwise the same conditions acetophenone adduct was obtained in 6% yield. Treatment of $BiCl_3$ with Zn(0) gave black powder immediately. Although details of the intermediate species are not at hand, a brief note by Nesmeyanov that $BiCl_3$ was reduced to Bi(0) by Zn(0) is informative.[11] Although the reaction mechanism is not yet clear at the present stage, we assume that some allylbismuth reagent (not allylzinc reagent) is formed through the oxidative addition of allylic halide to Bi(0) formed in situ.

Table 2. $BiCl_3$-Zn(0) Mediated Synthesis of Homoallylic Alcohols[a)]

Run	Allylic halide	Aldehyde	Yield of 3(%)[b)]
1	CH_2=$CHCH_2Br$	PhCHO	99
2	CH_2=$CHCH_2Br$	$Ph(CH_2)_7CHO$	99
3	CH_2=$CHCH_2Br$	$CH_3(CH_2)_7CHO$	71
4	CH_2=$CHCH_2Br$	*p*-ClC_6H_4CHO	91
5	CH_2=$CHCH_2Br$	CH_3CH=$CHCHO$	99[c)]
6	CH_2=$CHCH_2Br$	$PhCOCH_3$	56

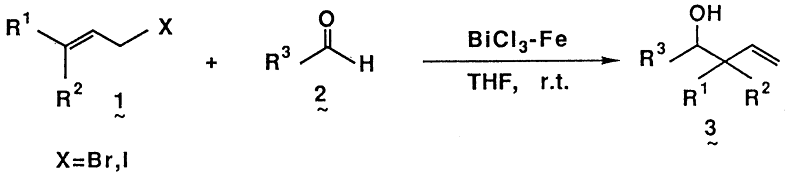
a) The molar ratio of an allylic halide : bismuth(III) chloride : zinc : aldehyde=1.2 : 1.2 : 1.8 : 1.0. b) Isolated yields are given unless otherwise stated. c) The extract from the reaction mixture was pure by ^{1}H NMR without purification. 1,2-Addition product was obtained.

Table 3. $BiCl_3$-Fe(0) Mediated Synthesis of Homoallylic Alcohols[a)]

Run	Allylic halide	Aldehyde	Product (%, yield)[b)]
1	CH_2=$CHCH_2Br$	PhCHO	 (92)
2	CH_2=$CHCH_2I$	PhCHO	 (99)
3	CH_3CH=$CHCH_2Br$[c)]	PhCHO	 (93, 85 : 15)[d)]
4	$(CH_3)_2C$=$CHCH_2Br$	PhCHO	 (80)
5	CH_2=$CHCH_2Br$	$Ph(CH_2)_2CHO$	 (91)
6	CH_2=$CHCH_2Br$	$CH_3(CH_2)_7CHO$	 (98)[e)]
7	CH_2=$CHCH_2Br$	CH_3CH=$CHCHO$	 (90)[e)]
8	CH_2=$CHCH_2Br$		 (96)

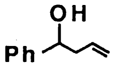
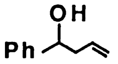
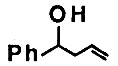
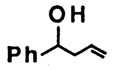
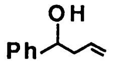
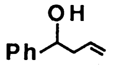
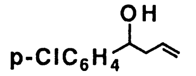
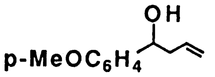
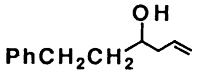
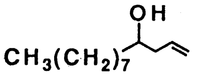
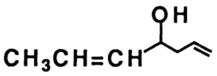
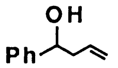
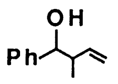
a) The molar ratio of an allylic halide : bismuth(III) chloride : iron : aldehyde=1.2 : 1.2 : 1.2 : 1.0. b) Isolated yields are given unless otherwise stated. c) A mixture of cis and trans isomers (30 : 70). d) The ratio of erythro : threo. Determined by ^{1}H NMR (the absorption of the methine proton H-C-OH)): erythro, δ=4.50 (d, J=5.7 Hz); threo, δ=4.30 (d, J=7.0 Hz) (Ref. 10c). e) The extract from the reaction mixture was pure by ^{1}H NMR without purification.

$BiCl_3$-Fe(0) Mediated Allylation of Aldehydes to Provide Homoallylic Alcohols. We found that treatment of $BiCl_3$ with Fe(0) gradually gave a black powder only, while with Zn(0) a black powder was found immediately. Therefore, we used Fe(0) instead of Zn(0) in the Method C and discovered $BiCl_3$-Fe(0) mediated allylation of aldehydes with allylic halides to homoallylic alcohols in THF (Method D). The

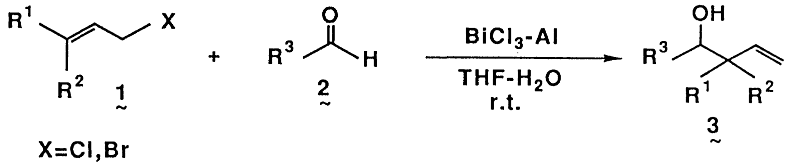


Scheme 4.

Table 4. $BiCl_3$-Al(0) Mediated Synthesis of Homoallylic Alcohols in Aqueous Solvent[a]

Run	Allylic halide	Aldehyde	Product (%, yield)[b]	
1	CH_2=$CHCH_2Br$	PhCHO		(70)[c,d]
2	CH_2=$CHCH_2Br$	PhCHO		(84)[c,e]
3	CH_2=$CHCH_2Br$	PhCHO		(88)[c,f]
4	CH_2=$CHCH_2Br$	PhCHO		(98)[c,g]
5	CH_2=$CHCH_2Br$	PhCHO		(88)[h]
6	CH_2=$CHCH_2Br$	PhCHO		(96)
7	CH_2=$CHCH_2Br$	*p*-ClC_6H_4CHO		(83)
8	CH_2=$CHCH_2Br$	*p*-$MeOC_6H_4CHO$		(68)
9	CH_2=$CHCH_2Br$	$PhCH_2CH_2CHO$		(91)
10	CH_2=$CHCH_2Br$	$CH_3(CH_2)_7CHO$		(70)
11	CH_2=$CHCH_2Br$	CH_3CH=$CHCHO$		(82)
12	CH_2=$CHCH_2Cl$	PhCHO		(30)
13	CH_3CH=$CHCH_2Br$[i]	PhCHO		(87, 84:16)[j]

a) For the reaction conditions unless otherwise stated, see the text. b) Isolated yields are given. c) The reaction solvent: THF (5 ml)-H_2O (1 ml). d) The number of mmoles of allyl bromide : bismuth(III) chloride : aluminum : benzaldehyde=2.4 : 2.4 : 2.4 : 2.0. e) The number of mmoles of allyl bromide : bismuth(III) chloride : aluminum : benzaldehyde=2.4 : 4.0 : 4.0 : 2.0. f) The number of mmoles of allyl bromide : bismuth(III) chloride : aluminum : benzaldehyde=3.0 : 3.0 : 3.0 : 2.0. g) The number of mmoles of allyl bromide : bismuth(III) chloride : aluminum : benzaldehyde=4.0 : 4.0 : 4.0 : 2.0. h) The reaction solvent: THF (2.5 ml)-H_2O (1 ml). The number of mmoles of allyl bromide: bismuth(III) chloride : aluminum : benzaldehyde=2.4 : 2.4 : 2.4 : 2.0. i) A mixture of cis and trans isomers (30 : 70). j) The ratio of erythro: threo. Determined by ^1H NMR (Ref. 10c).



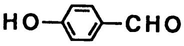
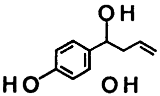
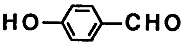
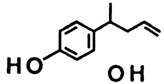
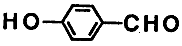
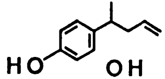
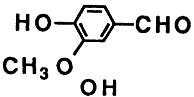
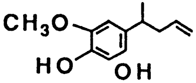
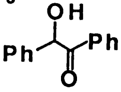
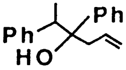
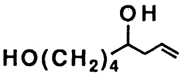
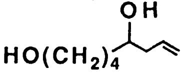
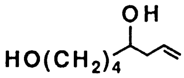
Scheme 5.

reaction was carried out as follows. A mixture of an allylic halide, an aldehyde, and $BiCl_3$ was treated with Fe(0) in THF at room temperature for 4—7 h. Typical results are summarized in Table 3.

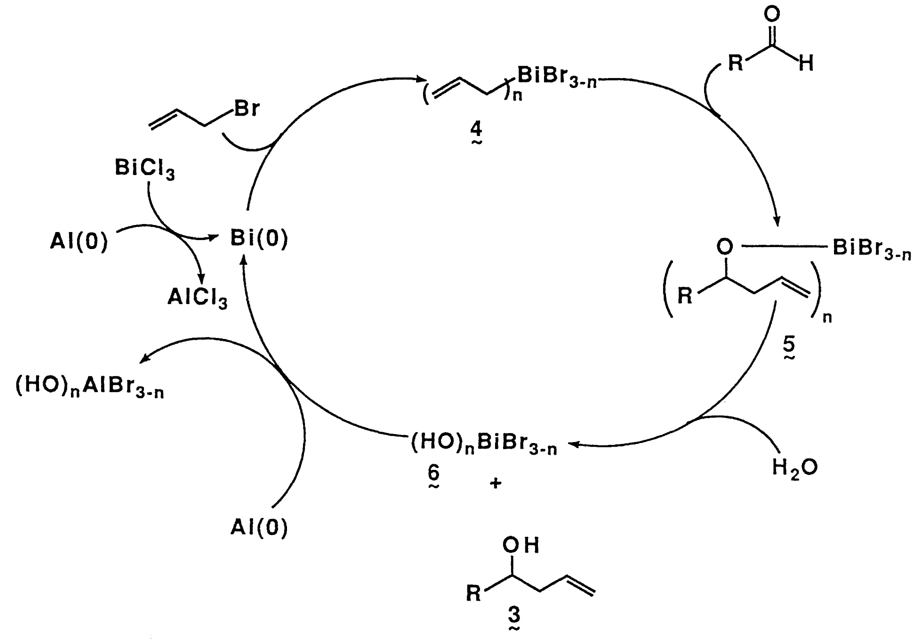
Hardly any expected product was obtained from allyl chloride, but both allyl bromide and allyl iodide themselves could be used as allylation reagents. The benzaldehyde/prenyl bromide reaction gave a satisfactory yield, different from Method A (vide supra), and the more substituted γ-carbon of an allyl group was attached regioselectively to carbonyl carbon (Run 4). The reaction of benzaldehyde with crotyl bromide gave predominant erythro selectivity regardless of the geometry of the crotyl unit (Run 3 and vlde infra).

$BiCl_3$-Al(0) Mediated Allylation of Aldehydes to Provide Homoallylic Alcohols in Aqueous Solvent.[12] Metallic aluminium has more enhanced metallic character than metallic zinc and metallic iron. Thus, we next tried the $BiCl_3$-Al(0) system in order to investigate for another bimetallic system. The desired homoallylic alcohol was not obtained at all in THF when Al(0) was used. Surprisingly, we found that a Barbier-type allylation of aldehydes with allylic halides could be easily effected in THF-H_2O (Method E).[13,14] In order to optimize the reaction conditions, the effect of the amount of THF-H_2O and the molar scales of the reactants were investigated (Runs 1—5). Allyl bromide gave the expected adduct in good yield, unlike the corresponding chloride. When an α,β-unsaturated aldehyde was used, the 1,2-addition product was obtained selectively (Run 11). Both aromatic and aliphatic aldehydes reacted smoothly to afford the corresponding homoallylic alcohols in good yields. The reaction of benzaldehyde with crotyl bromide gave predominant erythro selectivity (Run 13). This shows essentially complete γ-addition of the bismuth reagent. The use of $BiCl_3$ is essential in this reaction, viz., hardly any expected product was obtained using a Bi(0)-Al(0) system in THF-H_2O (vide supra). $BiCl_3$ did not promote the allylation at all in the absence of Al(0), and the action of Al(0) alone gave none of the desired products. Although details of the intermediate species of this reaction are not yet known, we assume that an allylbismuth reagent is formed through the oxidative addition of an allylic halide to Bi(0) generated by the reduction of $BiCl_3$ with Al(0).

Table 5. Allylation of Aldehydes Containing a Hydroxyl Group

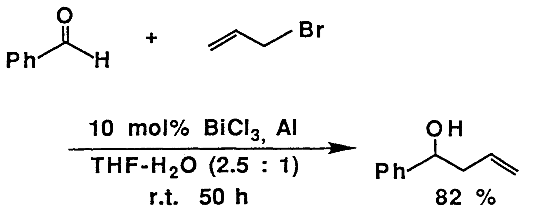
Run	Allyl halide	Aldehyde	Method	Product (%, yield)[a]	
1	$CH_2=CHCH_2Br$		A		(76)
2	$CH_2=CHCH_2Br$		C		(49)
3	$CH_2=CHCH_2Br$		D		(81)
4	$CH_2=CHCH_2Br$		A		(85)[b]
5	$CH_2=CHCH_2Br$		C		(75)
6	$CH_2=CHCH_2Br$	HO(CH₂)₄CHO	A		(80)[b]
7	$CH_2=CHCH_2Br$	HO(CH₂)₄CHO	C		(45)
8	$CH_2=CHCH_2Br$	HO(CH₂)₄CHO	D		(64)

a) Isolated yield are given unless otherwise stated. b) The extract from the reaction mixture was pure by ¹H NMR without purification.



Scheme 6. Proposed Mechanism of Catalytic $BiCl_3$ Mediated Allylation

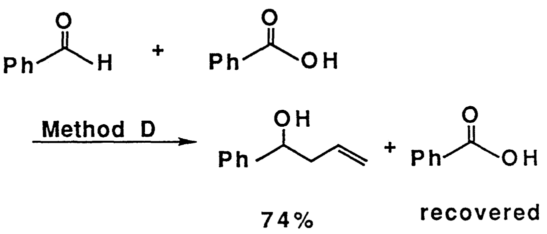
It is noteworthy that only a catalytic amount of $BiCl_3$ was needed to effect the present reaction. The benzaldehyde (2.0 mmol)-allyl bromide (2.4 mmol) reaction using $BiCl_3$ (0.24 mmol) and Al (0.08 g) gave 82% yield of the corresponding homoallyl alcohol after stirring for 50 h as shown below.



(2)

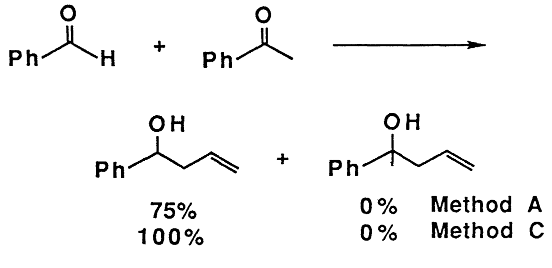
Although the reaction mechanism of the catalytic $BiCl_3$ mediated allylation is not clear, a catalytic cycle can be presumed in which some allylbismuth reagent (**4**) prepared via the proposed mechanism as mentioned above, reacts with an aldehyde to give **5**. Hydrolysis of **5** with H_2O yields a homoallylic alcohol (**3**) and bismuth(III) compound (**6**), which is reduced by Al(0), regenerating the Bi(0) catalyst.

Chemoselectivity. A striking feature of the present reaction is the high chemoselectivity. Noteworthy is the fact that the corresponding homoallylic alcohols were obtained from aldehydes containing a hydroxyl group using one equivalent of allylation reagent (Table 5), which may signify that some allylbismuth reagent prepared in situ does not react with a hydroxyl group. Furthermore, one equivalent of allylation reagent reacted with benzaldehyde even if benzoic acid was present in the reaction mixture, and benzoic acid was recovered intact.

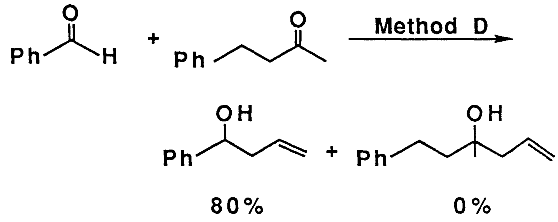


(3)

When acetophenone was used, Method A gave the desired product only in <5% yield estimated by ^{1}H NMR, and it was not obtained in any significant amount by Method B and D,[15] while it was obtained in 56% yield by Method C (vide supra). Based on this reactivity difference between aldehydes and ketones, we could discriminate benzaldehyde from acetophenone or 4-phenyl-2-butanone (Eqs. 4, 5).

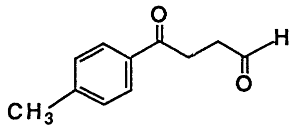


(4)

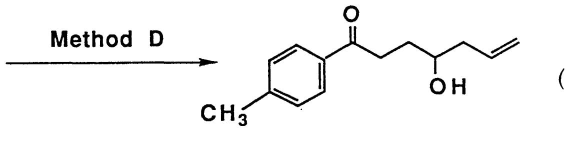


(5)

When keto aldehyde (**7**) was used, secondary homoallylic alcohol (**8**) was obtained in 50% unoptimized yield. Thus, the reaction proceeds selectively on an aldehyde carbon but not on a ketone carbon.



7



8 50% (6)

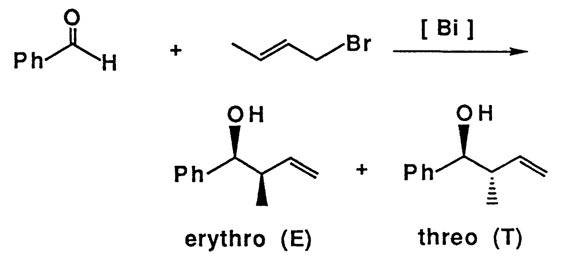
Table 6. Stereoselectivity of the Bismuth-Promoted Allylation (Eq. 7)

Run	Method (solvent)	E : T	Yield/%
1	B (DMF)	77 : 23	64
2	C (THF)	81 : 19	87
3	D (THF)	85 : 15	93
4	E (THF-H_2O)	84 : 16	87
5	D (MeOH)	85 : 15	81
6	D (DME)	88 : 12	100
7	D (EtOH)	89 : 11	100
8	D (DMF)	90 : 10	94
9	D (THF, $BF_3\cdot OEt_2$)[a]	89 : 11	100
10	D (THF, $BF_3\cdot OEt_2$)[b]	92 : 8	92

a) One equivalent of $BF_3\cdot OEt_2$ was used. b) Two equivalents of $BF_3\cdot OEt_2$ were used.

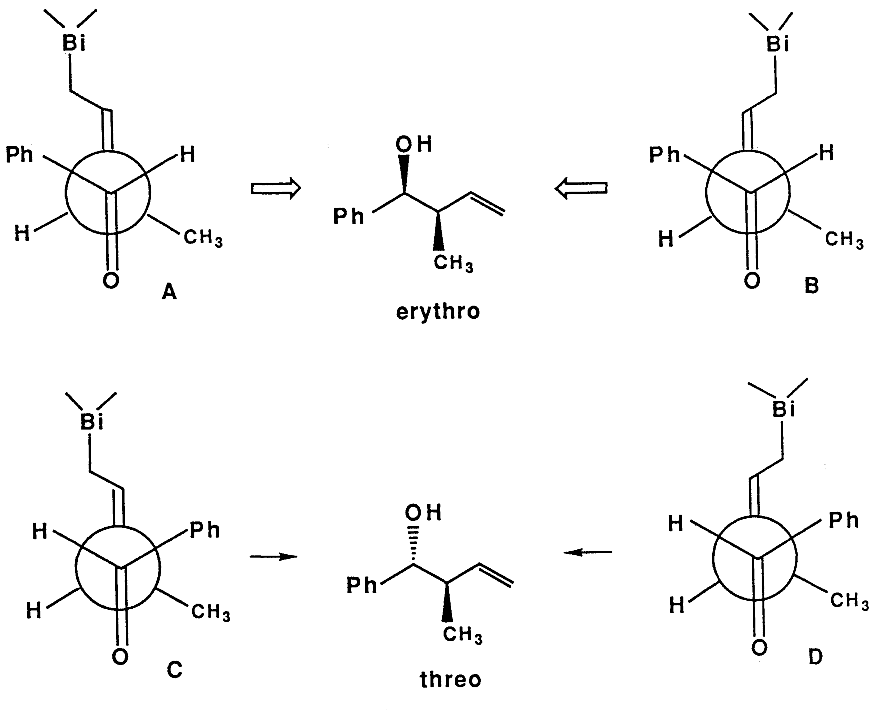
Functionalized compounds other than aldehydes and ketones are unreactive toward the allylation reagent. Namely, nitriles and esters were recovered unchanged. Another characteristic of the present reaction is that alkyl and aryl halides are unreactive toward bismuth, and therefore further applications for selective carbon-carbon bond formation will be found.

Stereoselectivity. We next investigated the stereoselectivity of the reaction of benzaldehyde with crotyl bromide [a mixture of cis and trans isomers (30 : 70)] as shown in Table 6.



(7)

In runs 1—4, Method D gave the best erythro selectivity and yield. Therefore, solvent effects using Method D were studied and it was found that DMF was a superior solvent to obtain the best erythro selectivity (Runs 5—8). It is particularly interesting that methanol and ethanol can be used as a reaction solvent (Runs 5 and 7). Recently, Grignard-type allylation of carbonyl compounds in methanol by the electrochemically recycled allylation reagent was reported.[5c] Finally, the reaction in the presence of two equivalents of $BF_3\cdot OEt_2$ in THF gave the highest erythro selectivity (Run 10), in sharp contrast to Sn–Al



Scheme 7.

[81% (yield), 87/22 (erythro/threo)],[5b] $MnCl_2$-$LiAlH_4$ (78%, 65/35),[10a] Sn (76%, 41/59),[5a] SnF_2 (85%, 35/65),[16] and $CrCl_3$-$LiAlH_4$ system (96%, 0/100).[10c] Our finding is comparable with erythro-selective addition of crotyltrialkyltins (cis and trans mixture) to aldehydes.[17] However, noteworthy is that the starting material is crotyl bromlde in our method.

Thus, the reaction of benzaldehyde with crotyl bromide gave predominant erythro selectivity although crotyl bromide is a mixture of cis and trans isomers (30 : 70). Although the reaction mechanism is not yet clear at present stage, we propose an acyclic transition state[1c,1d,17] for the stereochemical rationalization as shown below and the present reaction system presumably does not involve a conventional cyclic mechanism.[1b,1c,18] Among several possible transition state geometries, two conformations (A and B) leading to the erythro alcohol must be favored for steric reasons in comparison with those (C and D) leading to the threo isomer.

Finally, the present reaction is the first example of the Grignard-type allylation of aldehydes with allylic halides using metallic bismuth, $BiCl_3$-Zn(0), or $BiCl_3$-Al(0). We found that bismuth element can be used for carbon-carbon bond forming reaction for the first time. We believe that the present reaction have potential utility in organic synthesis.

Experimental

General Methods. Infrared spectra were recorded on a Hitachi 215 spectrophotometer. ^{1}H NMR spectra were recorded with Hitachi R-90H spectrometer and chemical shifts (δ) were reported in ppm using internal tetramethylsilane. Commercially available bismuth shot (99.999%, Wako Pure Chemical Industries, Ltd.) was scraped with a rasp. Bismuth powder (100 mesh, 99.999%, Aldrich Chemical Co.) is also effective and more convenient for the reaction. Bismuth(III) chloride, metallic zinc, iron, and aluminium were commercial materials and used without further purification. Allylic halides and aldehydes were distilled before use.

General Procedure of Method A. An allylic halide (2.2 mmol) was treated with metallic bismuth (0.46 g) in DMF (5 ml) under nitrogen at room temperature for 4 h. To the resulting greenish suspension was added an aldehyde (2.0 mmol). After stirring at room temperature for 2 h, the reaction mixture was quenched with a saturated aqueous ammonium chloride solution, and the organic materials were extracted with Et_2O (20 ml × 3). After drying the ether layer over anhydrous $MgSO_4$, the solvent was evaporated in vacuo. The desired product was isolated by preparative TLC on silica gel.

General Procedure of Method B (Barbier-type reaction). To metallic bismuth (0.46 g) in DMF (5 ml) were added an allylic halide (2.2 mmol) and an aldehyde (2.0 mmol) using a syringe under nitrogen at room temperature. The mixture was stirred for 12 h at that temperature. The procedures of workup and purification were the same as those of Method A described above.

General Procedure of Method C. Bismuth(III) chloride (2.4 mmol) was placed in a 50 ml two-necked flask and dried in vacuo by heating. Metallic zinc powder (0.24 g) was added under nitrogen along with anhydrous THF (5 ml), and the mixture was stirred for 1 h. To the resulting black suspension were added an allylic halide (2.4 mmol) and an aldehyde (2.0 mmol) using a syringe. The reaction mixture was stirred for 2 h at room temperature and the procedures of workup and purification were the same as those of Method A described above.

General Procedure of Method D. Bismuth(III) chloride (2.4 mmol) was placed in a 50 ml two-necked flask and dried in vacuo by heating. Metallic iron (0.13 g) was added under nitrogen and anhydrous THF (5 ml) was introduced. Then, using a syringe an allylic halide (2.4 mmol) and an aldehyde (2.0 mmol) were added at room temperature, and the reaction mixture was stirred for 4.5 h at that temperature. The procedures of workup and purification were the same as those of Method A described above.

General Procedure of Method E. Into a mixture of commercial grade Al powder (0.13 g) and $BiCl_3$ (2.4 mmol) was added THF (2.5 ml) and H_2O (1 ml) (this reaction is exothermic). Then, an aldehyde (2.0 mmol) and an allylic halide (2.4 mmol) were added using a syringe under nitrogen at room temperature, and the reaction mixture was stirred at room temperature for 10—20 h. The procedures of workup and purification were the same as those of Method A described above.

Spectral data of homoallylic alcohols are as follows.

1-Phenyl-3-buten-1-ol: Purified by thin-layer chromatography (SiO_2, hexane : AcOEt=9 : 1); IR (neat) 3400, 1640, 1500, 1450, 1040, 910, 750, and 700 cm^{-1}; ^{1}H NMR (CCl_4) δ=2.28 (s, 1H), 2.45 (dd, 2H, J=6.5, 6.5 Hz), 4.60 (t, 1H, J=6.5 Hz), 4.78—5.20 (m, 2H), 5.35—6.10 (m, 1H), and 7.22 (s, 6H). This product was also identified by comparison with an authentic sample prepared from allyl bromide and benzaldehyde using Zn(0).[4a]

1-Phenyl-5-hexen-3-ol: Purified by thin-layer chromatography (SiO_2, hexane : AcOEt,=12 : 1). This product was identified by comparison with an authentic sample.[5a]

1-(4-Methoxyphenyl)-3-buten-1-ol: Purified by thin-layer chromatography (SiO_2, hexane : AcOEt=9 : 1). This product was identified by comparison with an authentic sample.[19]

1-Dodecen-4-ol: Purified by Kugelrohr distillation. This product was identified by comparison with an authentic sample.[19]

2-Methyl-5-hexen-3-ol: Purified by thin-layer chromatography (SiO_2, hexane : AcOEt=9 : 1); IR (neat) 3350, 2905, 2860, 1640, 1450, 980, and 900 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=0.92 (d, 6H, J=6.5 Hz), 1.40—2.42 (m, 4H), 3.20—3.60 (m, 1H, 4.95—5.20 (m, 2H), 5.60—6.09 (m, 1H). This product was also identified by comparison with an authentic sample prepared from the known procedure.[5a]

1,5-Heptadien-4-ol: The extract from the reaction mixture was pure without purification. This product was identified by comparison with an authentic sample.[5b]

1-(4-Chlorophenyl)-3-buten-1-ol: Purified by thin-layer chromatography (SiO_2, hexane : AcOEt=9 : 1). This product was identified by comparison with an authentic sample.[5a]

1-Phenyl-2,2-dimethyl-3-buten-1-ol: Purified by thin-layer chromatography (SiO_2, hexane : AcOEt=9 : 1). This product was identified by comparison with an authentic sample.[10a)]

1-Phenyl-1-methyl-3-buten-1-ol: Purified by thin-layer chromatography (SiO_2, hexane : AcOEt=9 : 1). This product was identified by comparison with an authentic sample.[5b,19)]

1-Phenyl-2-hexyl-1,5-hexadien-3-ol: Purified by thin-layer chromatography (SiO_2, hexane : AcOEt=9 : 1); ^{1}H NMR ($CDCl_3$) δ=0.85 (t, 3H, J=6.0 Hz), 1.05—2.65 (m, 13H), 4.22 (t, 1H, 5.0 Hz), 5.05—5.29 (m, 2H), 5.60—6.00 (m, 1H), 6.50 (s, 1H), and 7.20 (s, 5H). This product was also identified by comparison with an authentic sample prepared from the known procedure.[5a)]

Preparation of Homoallylic Alcohols from Aldehydes Containing a Hydroxyl Groups. By use of Methods A, C, and D described above, the corresponding homoallylic alcohols were obtained from aldehyde containing a hydroxyl group using one equivalent of allylation reagent. The crude product was purified by thin-layer chromatography (SiO_2, hexane : AcOEt=3 : 2).

1-(4-Hydroxylphenyl)-3-buten-1-ol: IR (neat) 3600—3000, 1600, 1500, 1220, 900, 820, and 720 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=2.47 (dd, 2H, J=7.0, 7.0 Hz), 2.70—3.80 (brs, 1H), 4.62 (t, 1H, J=7.0 Hz), 4.85—5.28 (m, 2H, 5.40—6.05 (m, 1H), 6.70 (d, 2H, J=9.0 Hz), 7.06 (d, 2H, J=9.0 Hz), and 7.30—8.10 (brs, 1H). This product was also identified by comparison with an authentic sample prepared from the known procedure.[5b)]

1,2-Diphenyl-4-pentene-1,2-diol: IR (KBr) 3450, 2900, 1620, 1490, 1440, 1260, 1060, 930, 880, and 700 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=2.55 (s, 1H) , 2.75 (d, 1H, J=4.0 Hz), 2.83 (dd, 2H, J=4.2, 1.0 Hz), 4.70 (d, 1H, J=4.0 Hz), 4.80—5.20 (m, 2H), 5.30—6.00 (m, 1H), and 7.03 (m, 10H). Anal. Calcd for $C_{17}H_{18}O_2$: C, 80.28; H, 7.13%. Found: C, 80.20; H, 7.25%.

7-Octene-1,5-diol: ^{1}H NMR ($CDCl_3$) δ=1.10—1.85 (m, 7H), 2.25 (dd, 2H, J=7.0, 7.0 Hz), 2.66 (brs, 1H), 3.35—3.80 (m, 3H), 4.90—5.20 (m, 2H), and 5.56—6.05 (m, 1H). This product was also identified by comparison with an authentic sample prepared from the known procedure.[5b)]

Allylation of Benzaldehyde in the Presence of Benzoic Acid by Method D. Bismuth(III) chloride (2.4 mmol) was placed in a 50 ml two-necked flask and dried in vacuo by heating. Metallic iron (0.13 g) and benzoic acid (2.0 mmol) were added under nitrogen, and anhydrous THF (5 ml) was introduced. Then, using a syringe allyl bromide (2.4 mmol) and benzaldehyde (2.0 mmol) were added at room temperature, and the reaction mixture was stirred for 4.6 h at that temperature. Workup was achieved according to the procedure of Method A. 1-Phenyl-3-buten-1-ol was isolated in 74% yield by thin-layer chromatography (hexane : AcOEt=9 : 1) and benzoic acid was recovered in 71%.

Allylation of Benzaldehyde in the Presence of Acetophenone by Method C. Bismuth(III) chloride (2.4 mmol) was placed in a 50 ml two-necked flask and dried in vacuo by heating. Metallic zinc powder (0.24 g) was added under nitrogen along with anhydrous THF (5 ml), and the mixture was stirred for 1 h. To the resulting black suspension were added benzaldehyde (2.0 mmol), acetophenone (2.0 mmol), and allyl bromide (2.4 mmol) using a syringe. The reaction mixture was stirred for 2 h at room temperature and worked up according to the procedure of Method A. Inspection of the extract by ^{1}H NMR revealed that acetophenone did not give the corresponding homoallylic alcohol at all. 1-Phenyl-3-buten-1-ol was isolated in quantitative yield by thin-layer chromatography (SiO_2, hexane : AcOEt=9 : 1).

Allylation of Benzaldehyde in the Presence of 4-Phenyl-2-butanone by Method D. Bismuth(III) chloride (2.4 mmol) was placed in a 50 ml two-necked flask and dried in vacuo by heating. Metallic iron (0.13 g) was added under nitrogen and anhydrous THF (5 ml) was introduced. Then, using a syringe benzaldehyde (2.0 mmol), 4-phenyl-2-butanone (2.0 mmol), and allyl bromide (2.4 mmol) were added at room temperature. The reaction mixture was stirred for 4.5 h at that temperature and worked up according to the procedure of Method A. Inspection of the extract by ^{1}H NMR revealed that 4-phenyl-2-butanone did not give the corresponding homoallyllc alcohol at all. 1-Phenyl-3-buten-1-ol was isolated in 80% yield by flash column chromatography (SiO_2, hexane : AcOEt=9 : 1).

Allylation of Keto Aldehyde (7). By using Method D, $BiCl_3$ (1.8 mmol), Fe (0.10 g), 4-oxo-4-*p*-tolylbutanal (1.5 mmol), and allyl bromide (1.8 mmol) were reacted in dry THF (5 ml). The procedure of workup was the same as that of Method D described above. The crude product was purified by thin-layer chromatography (SiO_2, hexane : AcOEt=2 : 1) to afford the corresponding homoallylic alcohol (**8**) in 50% yield. IR (neat) 3450, 2900, 1670, 1605, 1400, 1180, 1040, 980, 910, and 810 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=1.60—2.50 (m, 5H), 2.40 (s, 3H), 3.11 (dd, 2H, J=7.0, 7.0 Hz), 3.73 (brs, 1H), 4.95—5.25 (m, 2H), 5.60—6.10 (m, 1H), 7.23 (d, 2H, J=7.0 Hz), and 7.82 (d, 2H, J=7.0 Hz). This product was also identified by comparison with an authentic sample prepared from the known procedure.[10b)]

Crotylation of Benzaldehyde. By using Method B, Method C, Method D, and Method E described above, benzaldehyde was reacted with crotyl bromide and the product was isolated by thin-layer chromatography (SiO_2, hexane : AcOEt=9 : 1) in good yield (see text). In the reaction utilizing $BF_3 \cdot OEt_2$, $BF_3 \cdot OEt_2$ was added before addition of benzaldehyde. The ratio of erythro–threo was determined by ^{1}H NMR (the absorption of the methine proton $\underline{H}$-C-OH) as follows. ^{1}H NMR ($CDCl_3$) δ=0.86 (threo) and 1.00 (erythro) (d, 3H, J=6.0 Hz), 2.15—2.70 (m, 2H), 4.30 (threo), and 4.50 (erythro) (d, 1H, J=7.0 Hz and 5.7 Hz), 4.80—5.22 (m, 2H), 5.50—5.95 (m, 1H), and 7.24 (s, 5H).[10c)]

References

1) a) G. Courtois and L. Miginlac, *J. Organomet. Chem.*, **69**, 1 (1974). For recent reviews, see: b) R. W. Hoffman, *Angew. Chem. Int. Ed. Engl.*, **21**, 555 (1982); c) Y. Yamamoto and K. Maruyama, *Heterocycles*, **18**, 357 (1982); d) Y. Yamamoto, *Acc. Chem. Res.*, **20**, 243 (1987).

2) W. G. Young, *Chem. Rev.*, **56**, 753 (1956).

3) T. Hiyama, M. Sawahata, and M. Obayashi, *Chem. Lett.*, **1983**, 1237.

4) a) K. Nutzel, "Methoden der Organischen Chemie," 4th ed., ed by Houben Weyl and E. Muller, Geog Thieme Verlag, Stuttgart (1973), Vol. 13/2a, p. 654. b) P. Christian and J. L. Luche, *J. Org. Chem.*, **50**, 910 (1985); c) C. Petrier, J. Einhorn, and J. L. Luche, *Tetrahedron Lett.*, **26**, 1449 (1985).

5) a) T. Mukaiyama and T. Harada, *Chem. Lett.*, **1981**, 1527; b) J. Nokami, J. Otera, T. Sudo, and R. Okawara, *Organometallics*, **2**, 191 (1983); c) K. Uneyama, H. Matsuda, and S. Torii, *Tetrahedron Lett.*, **25**, 6017 (1984).

6) Y. Butsugan, H. Ito, and S. Araki, *Tetrahedron Lett.*, **28**, 3707 (1987).

7) a) T. Imamoto, Y. Hatanaka, Y. Tawarayama, and M. Yokoyama, *Tetrahedron Lett.*, **22**, 4987 (1981); b) T. Imamoto, T. Kusumoto, Y. Tawarayama, Y. Sugiura, T. Mita, Y. Hatanaka, and M. Yokoyama, *J. Org. Chem.*, **49**, 3904 (1984).

8) Recently, Barton reported the functional group oxidation and the phenylation by pentavalent organobismuth reagents. D. H. R. Barton and J-P. Finet, *Pure Appl. Chem.*, **59**, 937 (1987) and references cited therein.

9) For a preliminary account of this study, see: a) M. Wada and K-y. Akiba, *Tetrahedron Lett.*, **26**, 4211 (1985); b) M. Wada, H. Ohki, and K-y. Akiba, *ibid.*, **27**, 4771 (1986); c) M. Wada, H. Ohki, and K-y. Akiba, *J. Chem. Soc. Chem. Commun.*, **1987**, 708.

10) Carbonyl addition of allyl unit with $MnCl_2$-$LiAlH_4$ or $CrCl_3$-$LiAlH_4$ has been reported. a) T. Hiyama, M. Obayashi, and A. Nakamura, *Organometallics*, **1**, 1249 (1982); b) Y. Okude, S. Hirano, T. Hiyama, and H. Nozaki, *J. Am. Chem. Soc.*, **99**, 3179 (1977); c) T. Hiyama, K. Kimura, and H. Nozaki, *Tetrahedron Lett.*, **22**, 1037 (1981).

11) A. N. Nesmeyanov, T. P. Tolstaya, and L. S. Isaeva, *Dokl. Akad. Nauk. S.S.S.R.*, **122**, 614 (1958), *Chem. Abstr.*, **53**, 4178 (1959).

12) In this connection, the benzaldehyde/allyl bromide (1 : 1 molar ratio) reaction by $BiCl_3$-Fe(0) took place even in aqueous media (THF-H_2O=10 : 1) to give the adduct in 44% yield for 17 h at room temperature.

13) Zn-mediated allylation of carbonyl compounds in aqueous media has been reported: see Refs. 4b and 4c.

14) Other similar allylations of aldehydes with allylic halides in aqueous media have been reported: a) using Sn-Al, see Ref. 5b; b) using $SnCl_2$-Al, K. Uneyama, N. Kamaki, A. Moriya, and S. Torii, *J. Org. Chem.*, **50**, 5396 (1985); K. Uneyama, H. Nambu, and S. Toril, *Tetrahedron Lett.*, **27**, 2395 (1986).

15) These are in sharp contrast to the findings that allylic metal reagents prepared in situ attack ketones, by Mn,3) Zn,4b) Sn,5) Ce,7b) $MnCl_2$-$LiAlH_4$,10a) or $CrCl_3$-$LiAlH_4$.10b,10c)

16) a) T. Harada, Ph. D. Thesis, University of Tokyo, 1982; b) T. Mukaiyama and T. Harada, unpublished; as mentioned in the Pacific Coast Lecture, Seattle, April 29, 1981.

17) a) Y. Yamamoto, H. Yatagai, Y. Naruta, and K. Maruyama, *J. Am. Chem. Soc.*, **102**, 7107 (1980); b) Y. Yamamoto, H. Yatagai, Y. Ishihara, N. Maeda, and K. Maruyama, *Tetrahedron*, **40**, 2239 (1984); c) For acyclic transition states of enolate reactions, see: S. Murata, M. Suzuki, and R. Noyori, *J. Am. Chem. Soc.*, **102**, 3248 (1980).

18) H. E. Zimmerman and M. D. Traxler, *J. Am. Chem. Soc.*, **79**, 1920 (1957), and Ref. 1.

19) T. Mukaiyama, T. Harada, and S-I. Shoda, *Chem. Lett.*, **1980**, 1507.