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Preparation of γ-Heterosubstituted Allylindium and Diindium Reagents and Their Reactions with Carbonyl Compounds

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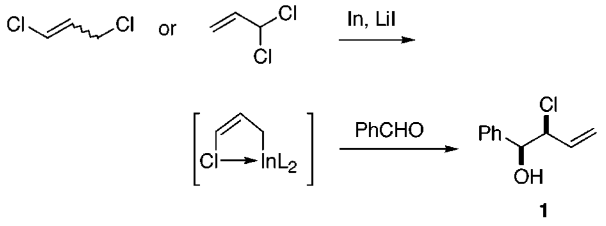
Various γ-heteroatom-substituted allylindium reagents were prepared, and their reactions with carbonyl compounds were examined. The reaction of 1,3-dibromopropene with metallic indium gave two types of organoindium species, γ-bromoallylindium and allylic diindium reagents. While the former gave 2-phenyl-3-vinyloxirane upon the coupling with benzaldehyde, the latter gave 1-phenylbut-3-en-1-ol. 1-Iodo-3-bromopropene gave the homoallylic alcohol exclusively. γ-Alkoxyallylindium reagents were prepared by treating the corresponding γ-alkoxyallyllithium with indium trichloride and reacted with benzaldehyde to give *vic*-diol mono ethers in high yields with good syn selectivity. γ-(Trimethylsilyl)allylindium and α,γ-disubstituted allylindium reagents were also prepared via transmetalation with the corresponding allyllithium.

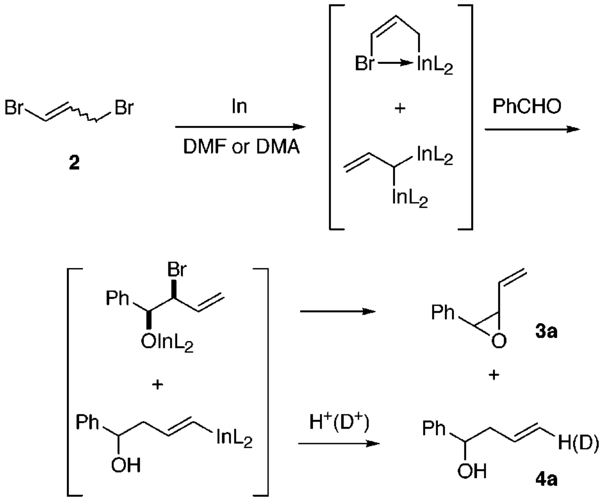
Introduction

Indium-mediated reactions have recently been focused in organometallic chemistry, and the preparations and synthetic applications of various allylindium reagents have been reported.[1] However, γ-heterosubstituted allylindium reagents have gathered very little attention in organic synthesis. Recently, we reported that γ-chloroallylindium can be prepared by the reaction of 1,3- or 3,3-dichloropropene with metallic indium in the presence of lithium iodide and that it gives chlorohydrin **1** in good yield with high syn selectivity upon the reaction with benzaldehyde[2,3] (Scheme 1). The indium-mediated reaction of 1,3-dibromopropene (**2**) with benzaldehyde gave *cis*-2-phenyl-3-vinyloxirane (**3a**) which is considered to come from the corresponding *syn*-bromohydrin[3] (Scheme 2). Homoallylic alcohol **4a** bearing no bromine atom was also obtained from the same reaction, and deuterium was incorporated when this reaction was quenched with DCl. On the basis of these results, we postulated the formation of γ-bromoallylindium and allylic *gem*-diindium reagents leading to **3a** and **4a**, respectively. To investigate the features of this reaction in detail, we have carried out the reaction by changing the reaction conditions as well as by using 3-bromo-1-iodopropene (**5**) in place of **2**. As further examples of γ-heterosubstituted allylindium reagents, γ-alkoxy- and γ-(trimethylsilyl)allylindium reagents have also been prepared and their reactions with carbonyl compounds have been investigated.

Scheme 1



Scheme 2



Results and Discussion

Indium-Mediated Reaction of 1,3-Dibromopropene with Carbonyl Compounds. In a previous paper,[3] we reported that the indium-mediated reaction of 1,3-dibromopropene (**2**) with benzaldehyde in DMF gave **3a** and **4a** together with a small amount (<5%) of diol **6**, which is the main product of the same reaction in aqueous media.[4] This reaction was examined by changing the solvent and the ratio of the reactants indium/**2**/benzaldehyde (Table 1). *N*,*N*-Dimethylacetamide (DMA) was found to give better results than DMF. Only **3a** and **4a** were obtained, and **6** did not form in DMA. As a small amount of bromohydrin was detected in the products, the reaction was quenched with diluted aqueous sodium hydroxide to convert the bromohydrin to **3a**. The product ratio **3a**/**4a** was found to be affected apparently by the

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(1) Cintas, P. *Synlett* **1995**, 1087−1096, and references therein.

(2) Araki, S.; Hirashita, T.; Shimizu, K.; Butsugan, Y. *Tetrahedron* **1996**, *52*, 2803−2816.

(3) Araki, S.; Hirashita, T.; Shimizu, H.; Yamamura, H.; Kawai, M. *Tetrahedron Lett.* **1996**, *37*, 8417−8420.

(4) Chen, D.-L.; Li, C.-J. *Tetrahedron Lett.* **1996**, *37*, 295−298.

10.1021/jo9816111 CCC: $18.00

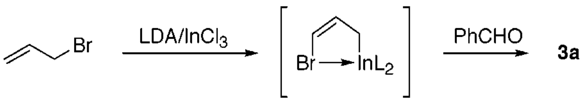
Table 1. Indium-Mediated Reaction of 1,3-Dibromopropene with Carbonyl Compounds[a]

$$\mathbf{2} + R^1COR^2 \xrightarrow[\text{DMA}]{\text{In}} \mathbf{3a\text{-}c} + \mathbf{4a\text{-}e}$$

	R^1COR^2				yield (%)		
entry	R^1	R^2	ratio[b]	method[c]	**3** (cis/trans)	**4**	ratio of **3**/**4**
1	Ph	H	1:2:1	A	**3a** 56 (90:10)	**4a** 30	74:26
2	Ph	H	1:1:1	A	**3a** 30 (87:13)	**4a** 28	52:48
3	Ph	H	2:2:1	A	**3a** 45 (94:6)	**4a** 31	59:41
4	Ph	H	4:2:1	A	**3a** 44 (94:6)	**4a** 39	53:47
5	Ph	H	1:2:1	B	**3a** 66 (93:7)	**4a** 20	77:23
6	Ph	H	2:2:1	B	**3a** 38 (96:4)	**4a** 42	48:52
7	Ph	H	4:2:1	B	**3a** 21 (97:3)	**4a** 46	31:69
8[d]	Ph	H	2:2:1	A	**3a** 45 (92:8)	**4a** 28	62:38
9[e]	p-$O_2NC_6H_4$	H	2:2:1	A	**3b** 35 (88:12)	**4b** 60	37:63
10[e]	n-C_7H_{15}	H	2:2:1	A	**3c** 25 (70:30)	**4c** 75	25:75
11[e]	(E)-PhCH=CH	H	2:2:1	A	0	**4d** 60	0:100
12[e]	Ph	Me	2:2:1	A	0	**4e** 40	0:100

[a] The reactions were carried out in DMA at 0 °C for 2 h unless otherwise noted. [b] Indium/**2**/R^1COR^2. [c] Method A: Indium and 1,3-dibromopropene were stirred for 1 h before the addition of a carbonyl compound. Method B: Indium, 1,3-dibromopropene, and a carbonyl compound were mixed together. [d] At −50 °C. [e] At room temperature.

Scheme 3



ratio of indium/**2** used. Although increasing the indium ratio increased the ratio of **4a** (Table 1, entries 1−3), the use of an excess of indium did not increase further the ratio of **4a** (Table 1, entry 4). When the reaction was carried out in a Barbier-type manner (Table 1, entries 5−7), a similar change of the ratio of **3a**/**4a** was observed. The stereoselectivity of **3a** and the ratio of **3a**/**4a** were not affected by the reaction temperature (Table 1, entry 8). This reaction did not occur in THF. Coupling with other carbonyl compounds was carried out under similar conditions (Table 1, entries 9−12). The reactions with p-nitrobenzaldehyde and octanal gave the corresponding homoallylic alcohols **4b** and **4c** in higher yields and higher selectivities compared with those of benzaldehyde. High cis selectivity was observed for oxiranes **3a** and **3b** from the aromatic aldehydes, whereas the cis selectivity for the aliphatic aldehyde was lower. The coupling with cinnamaldehyde and acetophenone yielded homoallylic alcohols **4d** and **4e** exclusively. Sterically demanding pivalaldehyde did not give the coupling products.

Preparation of γ-Bromoallylindium Reagents. Although γ-bromoallylindium was not obtained exclusively from the reaction of **2**, it could alternatively be prepared by the deprotonation of allyl bromide with LDA followed by transmetalation with indium trichloride. The γ-bromoallylindium thus prepared reacted with benzaldehyde to give **3a** exclusively in 72% (cis/trans = 83:17) (Scheme 3). It is known that allylic indium sesquibromides bearing alkyl- or aryl-substitutent(s) on the γ-carbon react with aldehydes to give *anti*-homoallylic alcohols unless the γ-substitutent is not sterically demanding.[5] On the contrary, the reaction of the allylindium reagents bearing chlorine or bromine at the γ-position gives *syn*-chlorohydrin or *cis*-oxirane stereoselectively.[2,3] The chlorine or bromine atom on the allylindium is expected to coordinate intramolecularly to indium forming a chelated five-membered ring. Consequently, (Z)-γ-chloro- and -bromoallylindium are considered to be more stable than the corresponding (E)-geometrical isomers.

Indium-Mediated Reaction of 3-Bromo-1-iodopropene with Carbonyl Compounds. The reaction of **5** and indium powder proceeded smoothly in DMA at room temperature. The resulting indium reagent was subjected to the reaction with benzaldehyde to give homoallylic alcohol **4a** exclusively (Table 2, entries 1−4). No halohydrin or vinyloxirane **3a** was formed. When this reaction was quenched with diluted DCl, deuterium was incorporated at the terminal (E)-vinyl position of **4a** (80%-d) (Table 2, entry 1), as was observed in the 1,3-dibromopropene case.[3] Attempts to trap this vinylindium reagent with chlorotrimethylstannane and iodine were failed. Although the reaction of **5** with indium metal was sluggish in THF and hence the yield of **4a** was low (Table 2, entry 5), it proceeded smoothly in an aqueous medium to give **4a** in high yield (Table 2, entry 6). Coupling with other carbonyl compounds was carried out under similar conditions (Table 2, entries 7−10). The reactions with acetophenone and 4-*tert*-butylcyclohexanone gave the corresponding homoallylic alcohols **4e** and **4f** in good yields (Table 2, entries 9 and 10), whereas no reaction proceeded with sterically demanding ketones such as diisopropyl ketone and camphor. In the case of 4-*tert*-butylcyclohexanone, the ratio of the product axial/equatorial alcohol (81:19) was almost coincident with that (82:18) of the reaction with allylindium sesquiiodide.[6]

Mechanistic Considerations. To explain the formation of homoallylic alcohol **4** in the reactions of **2** and **5**, we proposed the intermediacy of the allylic diindium intermediate.[3] Another mechanism involving a transformation of the initially formed bromohydrin indium salt to allylic indium species is unlikely (Scheme 4). This tandem reaction should give homoallylic alcohol with D on the internal carbon and/or allylic alcohol with D at the terminal carbon upon quenching with DCl. If γ-bromoallylindium could react with benzaldehyde at the α-position, homoallylic alcohol containing bromine at the olefinic terminal carbon would be formed (Scheme 5). If the bromine atom is replaced by indium, the resulting

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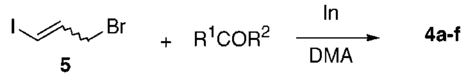
(5) (a) Isacc, M. B.; Chan, T.-H. *Tetrahedron Lett.* **1995**, *36*, 8957−8960. (b) Kirihara, M.; Takuwa, T.; Takizawa, S.; Momose, T. *Tetrahedron Lett.* **1997**, *38*, 2853−2854.

(6) Araki, S.; Ito, H.; Butsugan, Y. *J. Org. Chem.* **1988**, *53*, 1831−1833.

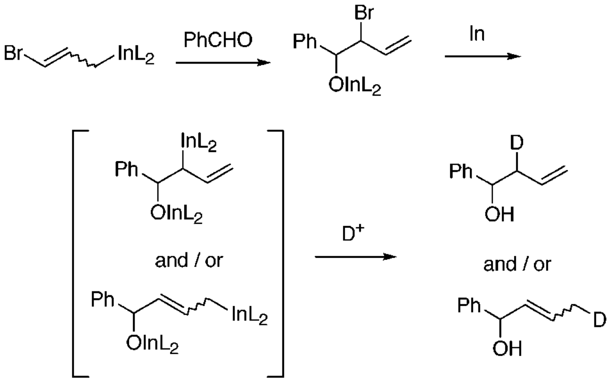
Table 2. Indium-Mediated Reaction of 3-Bromo-1-iodopropene with Carbonyl Compounds[a]



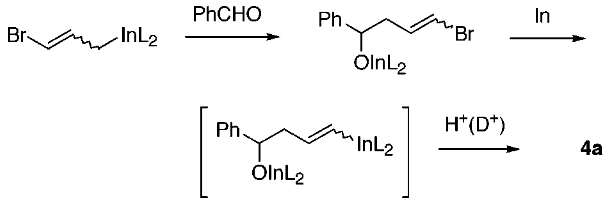
entry	R¹COR²		ratio[b]	solvent	product	yield (%)
	R¹	R²				
1[c]	Ph	H	2:2:1	DMA	**4a**-*d*	77 (80%-*d*)
2	Ph	H	3:2:1	DMA	**4a**	85
3	Ph	H	4:2:1	DMA	**4a**	84
4	Ph	H	2:1:1	DMA	**4a**	89
5	Ph	H	2:1:1	THF	**4a**	31
6[d]	Ph	H	2:2:1	H_2O/THF[e]	**4a**	90
7	n-C_7H_{15}	H	2:2:1	DMA	**4c**	70
8	(*E*)-PhCH=CH	H	2:2:1	DMA	**4d**	68
9	Ph	Me	2:2:1	DMA	**4e**	71
10	4-*tert*-butylcyclohexanone		2:2:1	DMA	**4f**	81[f]

[a] All reactions were carried out as described in Experimental Section. [b] Indium/**5**/aldehyde. [c] Quenched with dilute DCl. [d] This reaction was carried out overnight at room temperature. [e] H_2O/THF = 1:1. [f] Axial/equatorial alcohol = 81:19.

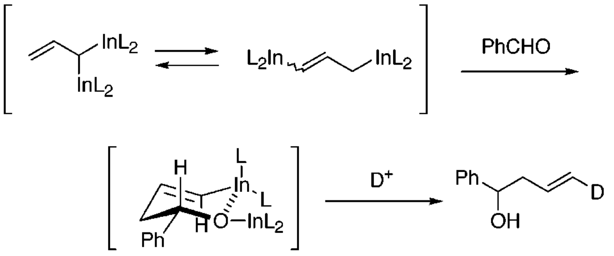
Scheme 4



Scheme 5

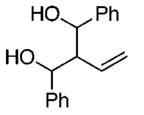


Scheme 6



vinylindium species would lead to **4a**. However, under the conditions employed here, an oxidative addition of indium to a carbon−halogen bond takes place only for activated halides such as allyl halides and benzyl halides. Therefore, this mechanism involving the conversion of vinylic bromide to vinylindium is difficult to explain the formation of **4a**. On the basis of the observation that the increase of the amount of indium increases the ratio of **4**/**3**, we conclude that the allylic diindium reagent is the most probable intermediate. The (*E*)-geometry of the D atom in compound **4a**-*d* can be reasonably explained by a six-membered coordination of the alkoxide oxygen to the vinylic indium atom (Scheme 6). The difficulty encountered in the displacement of the indium atom with electrophiles such as chlorostannane and iodine may come from this intramolecular coordination. The coordination of the alkoxide oxygen to the vinylic indium in the homoallylic alkoxide would prevent the attack of the electrophiles as was observed in a vinylzinc case.[7]

It was reported that **2** reacts with two molecules of aldehyde in the presence of indium metal in aqueous media to give diol **6**.[4] Although the indium-mediated reaction of **2** with aldehydes proceeds in both organic and aqueous media, the reaction courses and intermediates have thus been found not to be same. Furthermore, we have demonstrated that the ratio of diindium/γ-haloallylindium increases by changing the halogen of dihalopropene from Cl to Br and I, and the unique allylic diindium reagent can be prepared exclusively starting with **5**. γ-Haloallylindium compounds are considered to be in equilibrium with α-haloallylindium, and α-iodoallylindium is converted to the allylic *gem*-diindium reagent most readily. Even in aqueous media, compound **5** gave **4** in high yield and **6** was not formed at all.



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Reaction of γ-Alkoxyallylindium Reagents with Aldehydes. The γ-methoxyallylindium reagent was prepared in THF by deprotonation of allyl methyl ether (**7a**) with *s*-butyllithium, followed by transmetalation with indium trichloride. Addition of benzaldehyde to this reagent afforded the corresponding diol mono ether **8a** in high yields (Table 3). We first investigated the effect of the ratio allyllithium/$InCl_3$. The best result was obtained with the ratio of allyllithium/$InCl_3$ of 3:1. When the ratio of $InCl_3$ was increased, the yield and syn selectivity were decreased (Table 3, entries 1, 3, and 5). In each case, the addition of TMEDA improved the yield and syn selectivity (Table 3, entries 2, 4, and 6). The addition of methanol or water prior to the reaction with benzaldehyde did not decrease the yield of **8a** (Table 3, entries 7 and 8). To examine the influence of solvents,

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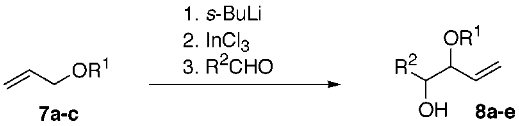
(7) Labaudinère, L.; Hanaizi, J.; Normant, J.-F. *J. Org. Chem.* **1992**, *57*, 6903−6908.

Table 3. Reaction of γ-Alkoxyallylindium Reagent with Carbonyl Compounds[a]



entry	**7**	R^1	R^2	molar ratio of **7**/$InCl_3$/R^2CHO	yield[b] (%) of **8**		syn/anti[c]
1	**7a**	Me	Ph	1:1:1	**8a**	46	70:30
2[d]	**7a**	Me	Ph	1:1:1	**8a**	55	83:17
3	**7a**	Me	Ph	3:1:1	**8a**	81	87:13
4[d]	**7a**	Me	Ph	3:1:1	**8a**	90	89:11
5	**7a**	Me	Ph	3:3:1	**8a**	55	69:31
6[d]	**7a**	Me	Ph	3:3:1	**8a**	89	88:12
7[e]	**7a**	Me	Ph	3:1:1	**8a**	84	87:13
8[f]	**7a**	Me	Ph	3:1:1	**8a**	80	61:39
9	**7a**	Me	(*E*)-PhCH=CH	3:1:1.5	**8b**	91	50:50
10[d]	**7a**	Me	(*E*)-PhCH=CH	3:1:1.5	**8b**	97	56:44
11	**7a**	Me	$CH_3(CH_2)_6$	3:1:1.5	**8c**	89	82:18
12	**7b**	*t*-Bu	Ph	3:1:1.5	**8d**	65	27:73
13[g]	**7b**	*t*-Bu	Ph	3:1:1.5	**8d**	75	40:60
14	**7c**	Ph	H	3:1:1.5	**8e**	41	

[a] All reactions were carried out as described in Experimental Section. [b] Based on R^2CHO. [c] Determined by ^1H NMR analysis. [d] TMEDA was added after the preparation of γ-alkoxyallylindium reagent. [e] Methanol (1 equiv) was added. [f] Excess (70-fold) water was added. [g] In H_2O/THF = 1:1.

THF was removed after the preparation of γ-methoxyallylindium and replaced with other solvents such as H_2O, CH_2Cl_2, and DMF. Although the same product **8a** was obtained in these solvents, both the yields (48, 60, and 52%, respectively) and syn selectivity (syn/anti = 48:52, 76:24, and 70:30, respectively) were decreased. The reaction with cinnamaldehyde and octanal also gave the corresponding monoprotected *vic*-diols **8b** and **8c** in high yields (Table 3, entries 9–11). However, the syn selectivity of **8b** was only modest and even the addition of TMEDA slightly improved the syn selectivity (Table 3, entry 10). With ketones no reaction proceeded. γ-*tert*-Butoxyallylindium also reacted with benzaldehyde to afford **8d** anti selectively (Table 3, entry 12). In an aqueous medium, the diastereoselectivity was diminished (Table 3, entry 13). γ-Phenoxyallylindium derived from allyl phenyl ether reacted with formalin to give **8e** (Table 3, entry 14).

Various γ-alkoxyallylmetal reagents have been used in organic synthesis.[8] Recently, Marshall reported that the reaction of α-alkoxyallylstannane with aldehydes in the presence of indium trichloride gave monoprotected *anti*-1,2-diols stereoselectively.[9] In this reaction, α-alkoxyallylstannane is considered to be converted to (*E*)-γ-alkoxyallylindium by means of S_E2' attack of indium trichloride, followed by the coupling with aldehydes via a sterically less demanding six-membered transition state leading to the anti products. On the contrary, our reaction of γ-methoxyallylindium prepared by the transmetalation from the corresponding allyllithium provided the monoprotected *syn*-1,2-diol on the reaction with benzaldehyde. Generally, the syn/anti selectivity depends on the geometry of the substituent at the γ-position of allylmetals. The syn selectivity observed in our reaction is considered to come from the (*Z*)-geometry of γ-methoxyallylindium. During the transmetalation step from γ-methoxyallyllithium which is known to possess the chelated (*Z*)-geometry,[8e] the geometry is preserved, and this gives the opposite syn selectivity to the reaction from α-alkoxyallylstannane. However, other factors such as the differences of the substituents on allylic systems and the reaction conditions (solvent and temperature) have to be taken into account. Indeed, sterically bulky *tert*-butoxyallylindium showed anti selectivity (Table 3, entries 12 and 13).

Concerning the coordination of oxygen atom to indium, Paquette reported successful stereoselective syntheses utilizing the coordinative nature of a neighboring oxygen atom.[10] According to the results shown in Table 3, the γ-methoxy group has sufficient coordination ability to indium in organic media. However, the intramolecular coordination to indium becomes less important in aqueous media, owing to the competition with the intermolecular coordination of water. Allylindium compounds are known as water-tolerable reagents. In fact, the coupling of γ-alkoxyallylindium with carbonyl compounds proceeded even in aqueous media, though the diastereoselectivity was somewhat diminished. γ-Alkoxyallylindium has now been found to possess typical characteristics of allylic indium reagents in respect of high γ-selectivity and stability under aqueous conditions.

Reaction of γ-Trimethylsilyl-Substituted Allylindium Reagents with Aldehydes. γ-(Trimethylsilyl)allylindium was prepared by deprotonation of allyltrimethylsilane with *n*-BuLi–TMEDA, followed by the addition of $InCl_3$. The reaction of this indium reagent with benzaldehyde did not proceed selectively, giving a mixture of homoallylic alcohol **9** and (*E*)- and (*Z*)-1-

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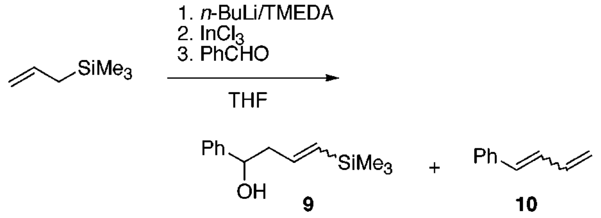
(8) For the reaction of γ-alkoxyallymetal reagents with carbonyl compounds, see: (Sn) (a) Koreeda, M.; Tanaka, Y. *Tetrahedron Lett.* **1987**, *28*, 143–146. (b) Marshall, J. A.; Luke, G. P. *J. Org. Chem.* **1991**, *56*, 483–485. (Al) (c) Koreeda, M.; Tanaka, Y. *J. Chem. Soc., Chem. Commun.* **1982**, 845–847. (d) Yamamoto, Y.; Yatagai, H.; Saito, Y.; Maruyama, K. *J. Org. Chem.* **1984**, *49*, 1096–1104. (B) (e) Brown, H. C.; Jadhav, P. K.; Bhat, K. S. *J. Am. Chem. Soc.* **1988**, 110, 1535–1538. (Fe) (f) Jiang, S.; Agoston, G. E.; Chen, T.; Cabal, M.-P.; Turos, E. *Organometallics* **1995**, *14*, 4697–4709.

(9) (a) Marshall, J. A.; Hinkle, K. W. *J. Org. Chem.* **1995**, *60*, 1920–1921. (b) Marshall, J. A.; Hinkle, K. W. *J. Org. Chem.* **1996**, *61*, 105–108. (c) Marshall, J. A.; Garofalo, A. W. *J. Org. Chem.* **1996**, *61*, 8732–8738.

(10) Paquette, L. A.; Bennett, G. D.; Issac, M. B.; Chhatriwalla, A. *J. Org. Chem.* **1998**, *63*, 1836–1845, and references therein.

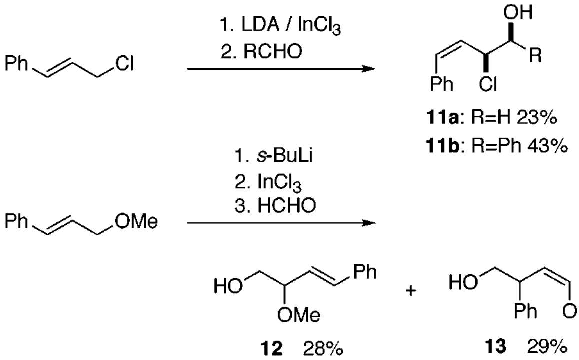
Table 4. Reaction of γ-(Trimethylsilyl)allylindium Reagents with Benzaldehyde[a]



entry	conditions	yield (%) 9 (*E*/*Z*)[b]	yield (%) 10 (*E*/*Z*)[b]
1	−78 °C, 2 h	11 (46:54)	28 (37:63)
2	reflux, 3 h	26 (38:62)	27 (17:83)

[a] All reactions were conducted as described in Experimental Section. [b] Based on ^{1}H NMR analysis.

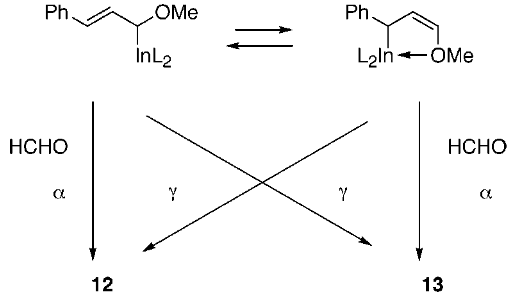
Scheme 7



phenylbut-1,3-diene (**10**) (Table 4). Changing the reaction temperature did not improve the regio- and stereoselectivity. 1,3-Diene **10** is considered to arise via a Peterson elimination of the initially formed homoallylic alcohol indium salt bearing a *vic*-trimethylsilyl group.

α,γ-Disubstituted Allylindium. The α,γ-disubstituted allylindium derived from cinnamyl chloride reacted with formaldehyde and benzaldehyde to give (*Z*)-chlorohydrin **11a** and **11b** highly regio- and diastereoselectively (Scheme 7). Only syn diastereomer **11b** was formed in the reaction with benzaldehyde. When the α,γ-disubstituted allylindium derived from cinnamyl methyl ether was employed, both the α- and γ-coupling products **12** and **13** were obtained in almost 1:1 ratio (Scheme 7). Both cinnamylindium and γ-methoxyallylindium react with aldehydes exclusively at the γ-position to afford the corresponding branched homoallylic alcohols. In the present α,γ-disubstituted case, two allylindium species, namely (*E*)-α-methoxy-γ-phenylallylindium and (*Z*)-γ-methoxy-α-phenylallylindium, are possibly formed through transmetalation (Scheme 8). The former is considered to give vinyl ether **13** via the γ-coupling with formalin, the latter provides monoprotected 1,2-diol **12**. Although products **12** and **13** could alternatively be formed via the α-coupling of the respective allylindium reagents, examples of α-coupling of allylic indium reagents are rare. On the contrary, the organoindium reagent derived from cinnamyl chloride gave chlorohydrin **11** regioselectively. This fact indicates that the equilibrium of α-chloro-γ-phenylallylindium and γ-chloro-α-phenylallylindium lies so far to the latter. It is interesting to note that the geometry of the styryl group is opposite between the products from cinnamyl methyl ether and from cinnamyl chloride: monoprotected (*E*)-diol **12** was obtained from cinnamyl methyl ether, whereas (*Z*)-chlorohydrin **11** was formed from cinnamyl chloride.

Scheme 8



Conclusion

γ-Halo- and γ-alkoxyallylindium reagents were prepared by the transmetalation of the corresponding allylic lithium compounds with $InCl_3$. These reagents coupled with carbonyl compounds at the γ-carbon syn selectively. On treatment with indium, dihalopropenes **2** and **5** gave the allylic *gem*-diindium reagent. Only few examples of allylic *gem*-dimetallic species are hitherto known such as zinc[11a] and tin compounds.[11b] The diindium species described in this paper is expected to be synthetically versatile and adds a new entry to this interesting family of organodimetallic reagents.

Experimental Section

All reactions were carried out in dry solvents under argon. Indium powder (99.99%) was obtained from Aldrich Chemical Co. 3-Bromo-1-iodopropene[12] and allyl *tert*-butyl ether[13] were prepared according to literature.

Reaction of 1,3-Dibromopropene (2) and Carbonyl Compounds. The following reaction with benzaldehyde (Table 1, entry 6) represents the general procedure. A mixture of indium powder (115 mg, 1.0 mmol), 1,3-dibromopropene (**2**) (100 μL, 1.0 mmol), and benzaldehyde (51 μL, 0.50 mmol) was stirred in DMA (2 mL) at 0 °C for 2 h. The reaction was quenched with 0.5 N sodium hydroxide. The product was extracted with diethyl ether. The extracts were washed with water and brine and dried over Na_2SO_4. After the solvent was removed under reduced pressure, the residue was purified by column chromatography on silica gel (elution with dichloromethane/hexane 1:1) to give 2-phenyl-3-vinyloxirane (**3a**)[14] (28 mg, 38%) and 1-phenylbut-3-en-1-ol (**4a**)[8f] (31 mg, 42%).

Products **3b**,[15] **3c**,[14] **4b**,[8f] **4c**,[16] **4d**,[16] **4e**,[16] and **4f**[16] are known compounds. The cis/trans ratio of oxiranes **3a−c** was determined on the basis of ^{1}H NMR.[17]

Reaction of γ-Bromoallylindium Derived from Allyl Bromide (Scheme 3). To freshly distilled diisopropylamine (0.5 mL, 2.9 mmol) in THF (5 mL) was added dropwise *n*-BuLi (1.6 M in hexane, 1.8 mL, 2.9 mmol) at 0 °C. The resulting pale yellow solution was stirred at 0 °C for 0.5 h. To a mixture of indium trichloride (222 mg, 1.0 mmol) and allyl bromide (250 μL, 3.0 mmol) in THF (4 mL) was added the freshly

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(11) For allylic geminal dimetallic species, see: (a) Marek, I.; Normant, J.-F. *Chem. Rev.* **1996**, *96*, 3241−3267. (b) Madec, D.; Férézou, J.-P. *Tetrahedron Lett.* **1997**, *38*, 6657−6660.

(12) Beruben, D.; Marek, I.; Normant, J.-F. *Tetrahedron* **1996**, *52*, 7235−7250.

(13) Schlosser, M.; Strunk, S. *Tetrahedron* **1989**, *45*, 2649−2664.

(14) Auge, J.; Davis, S. *Tetrahedron Lett.* **1983**, *24*, 4009−4012.

(15) Osuka, A.; Suzuki, H. *Tetrahedron Lett.* **1983**, *24*, 5109−5112.

(16) Araki, S.; Ito, K.; Butsugan, Y. *Appl. Organomet. Chem.* **1988**, 475−478.

(17) Furuta, K.; Ikeda, Y.; Meguriya, N.; Ikeda, N.; Yamamoto, H. *Bull. Chem. Soc. Jpn.* **1984**, *57*, 2781−2790.

prepared LDA dropwise at -78 °C. The suspension was stirred at -78 °C for 0.5 h, and then benzaldehyde (154 μL, 1.5 mmol) was added. The mixture was gradually warmed to room temperature over 2 h, and the reaction was quenched with saturated aqueous ammonium chloride. The product was extracted with ether, washed with water and brine, and dried over Na_2SO_4. The solvent was removed under reduced pressure, and the crude product was purified by column chromatography on silica gel (elution with EtOAc/hexane 1:9) to give **3a** (160 mg, 72%). The cis/trans ratio was 83:17 on the basis of ^{1}H NMR analysis.

Reaction of 3-Bromo-1-iodopropene (5) and Carbonyl Compounds. The following reaction (Table 2, entry 1) represents the general procedure. Indium powder (158 mg, 1.4 mmol) and 3-bromo-1-iodopropene (**5**) (141 μL, 1.4 mmol) were stirred in DMA (2 mL) at 0 °C for 1 h. Benzaldehyde (71 μL, 0.70 mmol) was added, and the mixture was stirred for another 1 h. The reaction was quenched with 1 M DCl in D_2O. The product was extracted with diethyl ether. The extracts were washed with water and brine and dried over Na_2SO_4. After the solvent was removed under reduced pressure, the residue was purified by column chromatography on silica gel (elution with dichloromethane) to give **4a**-*d* (79 mg, 77%). The deuterium content was confirmed to be 80% by ^{1}H NMR and MS.

(*E*)-[4-D]-1-Phenylbut-3-en-1-ol (4a-*d*): ^{1}H NMR (200 MHz, $CDCl_3$) δ 1.85$-$1.95 (bs, 1H), 2.47$-$2.56 (m, 2H), 4.70$-$4.78 (m, 1H), 5.16 (dt, $J = 17.0$, 2.8 Hz, 1H), 5.73$-$5.91 (m, 1H), 7.14$-$7.38 (m, 5H).

Reaction of γ-Alkoxyallylindium with Carbonyl Compounds. The following reaction (Table 3, entry 4) represents the general procedure. To a solution of allyl methyl ether (**7a**) (141 μL, 1.5 mmol) in THF (2 mL) was slowly added *s*-butyllithium in cyclohexane (1.0 M) (1.5 mL, 1.5 mmol) at -78 °C. After 1 h of stirring, a solution of indium trichloride (111 mg, 0.50 mmol) in THF (4 mL) and TMEDA (0.3 mL, 2.0 mmol) was added, and the mixture was kept at this temperature for 0.5 h. Benzaldehyde (51 μL, 0.50 mmol) was added, and the reaction was continued for 1 h. The reaction was quenched with dilute hydrochloric acid, and the product was extracted with diethyl ether. The organic extracts were washed with water and brine and dried over Na_2SO_4. The solvent was removed under reduced pressure, and the crude product was purified by flash column chromatography on silica gel (elution with EtOAc/hexane 1:9 then 2:8) to give **8a**[8f] (80 mg, 90%) as a mixture of diastereomers (syn/anti = 89:11). The syn/anti ratio was determined on the basis of ^{1}H NMR analysis.[8f]

4-Methoxy-1-phenylhexa-1,5-dien-3-ol (8b): IR (neat, cm^{-1}) 3450, 1600, 1444, 1100; ^{1}H NMR (200 MHz, $CDCl_3$) δ major isomer 2.91 (d, $J = 2.7$ Hz, 1H), 3.35 (s, 3H), 3.49 (t, $J = 7.6$ Hz, 1H), 4.15$-$4.22 (m, 1H), 5.27$-$5.38 (m, 2H), 5.60$-$5.86 (m, 1H), 6.21 (dd, $J = 16.0$, 6.1 Hz, 1H), 6.63 (d, $J = 16.0$ Hz, 1H), 7.18$-$7.42 (m, 5H); minor isomer 2.39 (d, $J = 5.4$ Hz, 1H), 3.70 (dd, $J = 7.7$, 4.0 Hz, 1H), 4.33$-$4.39 (m, 1H), 6.15 (dd, $J = 16.0$, 6.6 Hz, 1H), 6.68 (d, $J = 16.0$ Hz, 1H); MS (CI) *m*/*z* 187 (M + H $-$ H_2O, 100%), 155 (30); HRMS (CI) calcd for $C_{13}H_{15}O$ (M + H $-$ H_2O) 187.1123, found 187.1125. Anal. Calcd for $C_{13}H_{16}O_2$: C, 76.44; H, 7.89. Found: C, 75.33, H, 7.81.

3-Methoxyundec-1-en-4-ol (8c): IR (neat, cm^{-1}) 3450, 1450, 1100; ^{1}H NMR (200 MHz, $CDCl_3$) δ major isomer 0.82$-$0.89 (m, 3H), 1.15$-$1.50 (m, 12H), 2.15 (br s, 1H), 3.30 (s, 3H), 3.49 (dd, $J = 8.5$, 3.7 Hz, 1H), 3.62$-$3.72 (m, 1H), 5.22$-$5.38 (m, 2H), 5.76 (ddd, $J = 17.1$, 10.5, 8.0 Hz, 1H); minor isomer 5.52$-$5.65 (m, 1H). Anal. Calcd for $C_{12}H_{24}O_2$: C, 71.94; H, 12.08. Found: C, 71.30, H, 12.18.

Products **8d**[18] and **8e**[19] are known compounds.

Reaction of γ-(Trimethylsilyl)allylindium with Benzaldehyde (Table 4, entry 2). To a solution of allyltrimethylsilane (238 μL, 1.5 mmol) in a mixture of dry THF (5 mL) and TMEDA (0.30 mL, 2.0 mmol) was added at *n*-butyllithium in hexane (1.6 M) (0.90 mL, 1.5 mmol) -78 °C. After 30 min of stirring, a solution of indium trichloride (111 mg, 0.50 mmol) in THF (5 mL) was added, and the mixture was stirred for additional 10 min. Benzaldehyde (156 μL, 1.5 mmol) was added, and reaction mixture was heated at reflux for 3 h. The reaction was quenched with saturated aqueous ammonium chloride and extracted with diethyl ether. The extracts were washed with water and brine and dried over Na_2SO_4. The solvent was removed under reduced pressure, and the crude product was purified by column chromatography on silica gel (elution with dichloromethane) to give **9**[8d] (86 mg, 26%) and **10**[20] (53 mg, 27%).

Reaction of the α,γ-Disubstituted Allylindium Reagent Derived from Cinnamyl Chloride (Scheme 7). To a suspension of indium trichloride (283 mg, 1.3 mmol) and cinnamyl chloride (303 μL, 2.2 mmol) in THF (4 mL) was added dropwise freshly prepared LDA (2.2 mmol) in THF (4 mL) at -78 °C. The suspension was stirred at -78 °C for 0.5 h, and benzaldehyde (103 μL, 1.0 mmol) was added. The mixture was gradually warmed to room temperature during 2 h and stirred overnight at room temperature. The reaction was quenched with saturated aqueous ammonium chloride, and the product was extracted with ether, washed with water and brine, and dried over Na_2SO_4. The solvent was removed under reduced pressure. The crude product was purified by column chromatography on silica gel (elution with EtOAc/hexane 1:9) to give **11b** (112 mg, 43%) as a single diastereomer. Similarly, coupling with formalin (37 wt %, 1.0 mL, 13 mmol) gave **11a**[2] in 23% yield (based on the cinnamyl chloride).

(*Z*)-2-Chloro-1-phenyl-4-phenylbut-3-en-1-ol (11b): IR (neat, cm^{-1}) 3350, 1630, 1498, 1456; ^{1}H NMR (200 MHz, $CDCl_3$) δ 2.09 (d, $J = 3.2$ Hz, 1H), 4.26 (dd, $J = 9.3$, 6.1 Hz, 1H), 4.97 (dd, $J = 6.1$, 3.2 Hz, 1H), 6.20 (d, $J = 7.5$ Hz, 1H), 6.31 (dd, $J = 9.3$, 7.5 Hz, 1H), 7.1$-$7.3 (m, 10H). Anal. Calcd for $C_{16}H_{15}ClO$: C, 74.27; H, 5.84. Found: C, 74.54, H, 5.84.

Reaction of α,γ-Disubstituted Allylindium Reagent Derived from Cinnamyl Methyl Ether (Scheme 7). To a solution of cinnamyl methyl ether (148 μL, 1.0 mmol) in THF (2 mL) was slowly added *s*-butyllithium in cyclohexane (1.0 M) (1.0 mL, 1.0 mmol) at -78 °C. After 30 min of stirring at this temperature, a solution of indium trichloride (90 mg, 0.4 mmol) in THF (2 mL) was added, and the mixture was kept at this temperature for 1 h. Formalin (37 wt %, 0.5 mL, 6.5 mmol) was added, and the reaction was continued overnight at room temperature. The reaction was quenched with dilute hydrochloric acid, and the products were extracted with ether. The organic extracts were washed with water and brine and dried over Na_2SO_4. The solvent was removed under reduced pressure, and the crude product was purified by flash column chromatography on silica gel (elution with EtOAc/hexane 1:9 then 2:8) to give **12**[21] (50 mg, 28%) and **13** (52 mg, 29%).

(*Z*)-4-Methoxy-2-phenylbut-3-en-1-ol (13): IR (neat, cm^{-1}) 3400, 1664, 1498, 1112; ^{1}H NMR (200 MHz, $CDCl_3$) δ 1.73 (t, $J = 6.5$ Hz, 1H), 3.63 (s, 3H), 3.68$-$3.82 (m, 2H), 3.91$-$4.04 (m, 1H), 4.57 (dd, $J = 9.0$, 6.4 Hz, 1H), 6.08 (dd, $J = 6.4$, 1.0 Hz, 1H), 7.15$-$7.45 (m, 5H). Anal. Calcd for $C_{11}H_{14}O_2$: C, 74.13; H, 7.92. Found: C, 73.99, H, 8.02.

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(18) Newcomb, M.; Le Tadic, M.-H.; Chesteny, D.-L.; Roberts, E. S.; Hollenberg, P. F. *J. Am. Chem. Soc.* **1995**, *117*, 12085$-$12091.

(19) Al'bitskaya, V. M.; Petrov, A. A.; Blyakman, E. M. *Zh. Obshch. Khim.* **1961**, *31*, 2166$-$2171; *Chem. Abstr.* **1962**, *56*, 2363f.

(20) Tsai, D. J. S.; Matteson, D. *Tetrahedron Lett.* **1981**, *22*, 2751$-$2752.

(21) Christie, S. D. R.; Cosset, C.; Hamilton, D. R.; Kerr, W. J.; O'Callaghan, M. *J. Chem. Soc., Chem. Commun.* **1995**, 2051$-$2052.