DOI: 10.1002/chem.201000523

Preparation of Organoaluminum Reagents from Propargylic Bromides and Aluminum Activated by $PbCl_2$ and Their Regio- and Diastereoselective Addition to Carbonyl Derivatives

Li-Na Guo, Hongjun Gao, Peter Mayer, and Paul Knochel*[a]

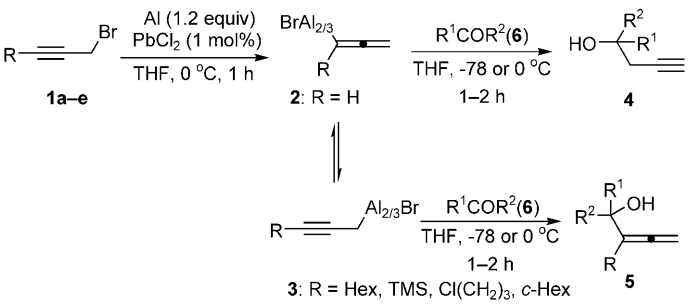
Dedicated to Professor José Barluenga on the occasion of his 70th birthday

Abstract: Various propargylic and allenic aluminum reagents have been easily prepared by a direct insertion of aluminum into propargylic bromides in the presence of $PbCl_2$ (1 mol%). These organoaluminum reagents react with carbonyl compounds to afford the corresponding allenic alcohols or homopropargylic alcohols in good to excellent yields with high regio- and diastereoselectivity.

Keywords: aluminum · diastereoselectivity · lead chloride · organoaluminum · propargylic bromide

Introduction

The preparation of organometallics by the oxidative addition of a metal to an organic halide is an important method, which has a good atom economy[1] and excellent generality. The metal activation is crucial for performing a direct insertion reaction of a metal to an organic halide. Rieke has shown that activated magnesium and activated zinc can be obtained by the reduction of magnesium or zinc halides with lithium metal.[2] Alternatively, we have shown that the addition of LiCl considerably facilitates the oxidative addition of Zn,[3] Mg,[4] and In[5] powder to various organic halides. Recently, we have reported that although the direct activation of Al with LiCl was not possible for reactions with unsaturated iodides or bromides, we have found that additional catalysis with small amounts of various salts such as $SnCl_4$, $SnCl_2$, $InCl_3$, $BiCl_3$, or $PbCl_2$[6] allows a smooth unprecedented direct insertion of Al powder to aryl bromides or iodides.[7] To our delight, we found that Al powder can also easily insert into propargylic bromides of type **1** in the presence of a catalytic amount of $PbCl_2$.[8] Depending on the nature of the substituent R, the organoaluminum reagent exists either as an allenic organometallic species of type **2** or as a propargylic organometallic species of type **3**. Their addition to carbonyl compounds (aldehydes or ketones), which proceeds via a six-membered cyclic transition state, gives the corresponding homopropargylic alcohols of type **4** or allenic alcohols of type **5** (Scheme 1).



Scheme 1. Selective synthesis of homopropargylic alcohol **4** or allenic alcohol **5** from propargylic bromide **1a–e**.

Thus, if R is a small group (R = H), the allenic aluminum isomer **2** is preferred, whereas if R is more sterically hindered (R ≠ H), a propargylic aluminum species of type **3** is favored.[9] Herein, we wish to report a detailed study of the regio- and diastereoselective addition of these organoaluminum species to carbonyl compounds such as aldehydes and ketones.

[a] Dr. L.-N. Guo, Dr. H. Gao, Dr. P. Mayer, Prof. Dr. P. Knochel
Department Chemie and Biochemie
Ludwig-Maximilians-Universität München
Butenandtstrasse 5-13, Haus F, 81377 München (Gemany)
Fax: (+49) 892-1807-7680
E-mail: paul.knochel@cup.uni-muenchen.de

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/chem.201000523.

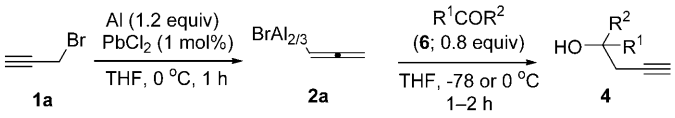
Results and Discussion

According to Gaudemar[10] and Eiter et al.,[11] allyl and propargyl aluminum derivatives are prepared by heating the corresponding bromides in THF to reflux with aluminum granules activated by a catalytic amount of $HgCl_2$.[10–12] Much milder conditions can be achieved by an appropriate activation of the aluminum surface.[13,14] Thus, we have found that the treatment of various propargylic bromides **1** with aluminum powder (1.2 equiv) in the presence of $PbCl_2$ (1 mol%) in THF at 0°C for 1 h readily produces the corresponding organoaluminum reagents of type **2** or **3**. This practical preparation encouraged us to investigate their additions to various aldehydes and ketones.

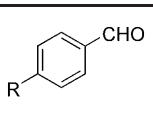
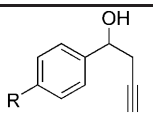
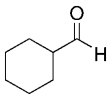
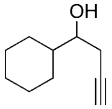
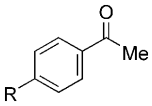
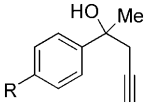
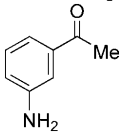
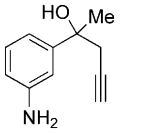
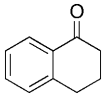
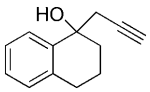
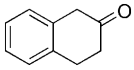
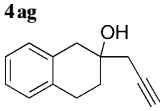
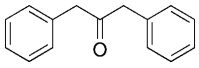
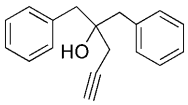
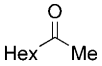
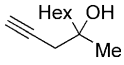
First, 3-bromo-1-propyne (**1a**, 2.0 mmol) was treated with aluminum powder (2.4 mmol) in the presence of $PbCl_2$ (0.02 mmol, 1 mol%) in THF (2 mL) at 0°C for 1 h, leading to the allenic aluminum reagent **2a**. Owing to this allenic structure, the addition to aldehydes and ketones via a six-membered cyclic transition state afforded only the homopropargyl alcohols **4aa**–**4aj** as sole products in 61–99% yield (Table 1).[15] Whereas aliphatic or aromatic aldehydes (**6a**–**d**) react with the allenyl-aluminum reagent **2a** at −78°C (1–2 h; Table 1, entries 1–4), this addition reaction requires 1–2 h at 0°C for ketones (**6e**–**j**; Table 1, entries 5–10). Remarkably, various functional groups such as ester, cyanide, or primary amino groups are well tolerated under these reaction conditions (Table 1, entries 2, 3, 5, and 6). Also, the presence of relatively acidic methylene groups such as in α- or β-tetralone (**6g** and **6h**) or 1,3-diphenylpropan-2-one (**6i**) are also tolerated. The addition reaction proceeds smoothly and no competitive deprotonation is observed. The desired homopropargylic alcohols **4ag**–**4ai** were obtained as sole products in 72–91% yield (Table 1, entries 7–9).

Furthermore, 3-substituted propargylic bromides **1b**–**e** can also readily be converted to the corresponding organoaluminum reagents under the same conditions. In this case, steric interactions disfavor the allenic form **2** and the propargylic aluminum species of type **3** are preferred (Scheme 1). Thus, after an addition reaction to carbonyl derivatives, the allenic alcohols of type **5** are produced as single products in most cases (Table 2). Thus, the organoaluminum species generated from 1-bromo-2-nonyne (**1b**; R = hexyl (Hex)) and (trimethylsilyl)propargyl bromide (**1c**; R = TMS)[9a] reacted with various aromatic and aliphatic ketones affording the allenic alcohols **5** as single isomers (Table 2, entries 1–4 and 6–11). No homopropargylic alcohols were observed in all of these cases. However, treatment of the aluminum reagent derived from **1b** with benzaldehyde (**6a**) gave a separable mixture of allenic alcohol **5ba** and homopropargyl alcohol **4ba** in 91% yield (86:14 ratio **5ba**:**4ba**; Table 2, entry 5). A similar mixture was obtained for the reaction of acetophenone (**6k**) with the organoaluminum reagents derived from 1-bromo-6-chloro-2-hexyne (**1d**; Table 2, entry 12) and (3-bromoprop-1-ynyl)cyclohexane (**1e**; Scheme 2). We envisioned that by increasing the steric hindrance of the other substituents attached to the aluminum center, we would favor the propargylic organometallic species (for example **3e** over **2e**; Scheme 2). Thus, we treated the aluminum reagent generated from **1b**, **1d**, and **1e** with a bulky arylmagnesium bromide (2,4,6-(iPr)$_3$C$_6$H$_2$MgBr; 0.7 equiv) at 0°C for 3 h, leading tentatively to the new aluminum reagents such as **7e** and **8e** (Scheme 2). Steric hindrance favors the regioisomeric organometallic species **8e**. This change allowed improved isomeric ratio. Thus, the product ratio between **4ek** and **5ek** went

Table 1. Addition of allenyl aluminum bromide (**2a**) to aldehydes and ketones leading to homopropargylic alcohols **4aa**–**4aj**.[a]

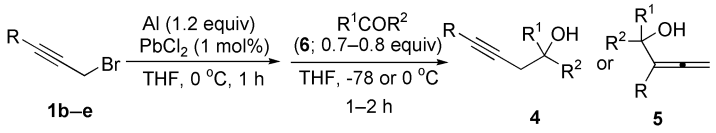


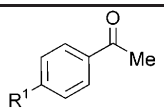
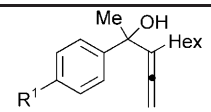
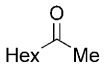
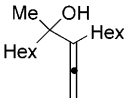
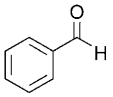
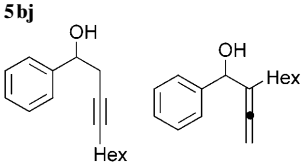
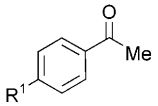
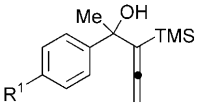
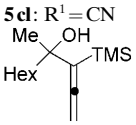
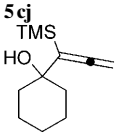
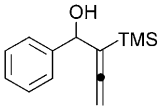
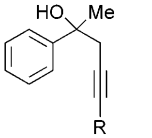
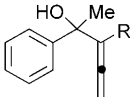
1a 2a 4

Entry	Aldehyde or Ketone	Product	Yield [%][b]
1			
	6a: R = H	**4aa**: R[1] = H	0[c], 87
2	**6b**: R = CO_2Me	**4ab**: R = CO_2Me	95
3	**6c**: R = CN	**4ac**: R = CN	92
4[d]			61
	6d	**4ad**	
5			99
	6e: R = CO_2Me	**4ae**: R = CO_2Me	
6			77
	6f	**4af**	
7			91
	6g	**4ag**	
8			72
	6h	**4ah**	
9			91
	6i	**4ai**	
10			95
	6j	**4aj**	

[a] All reactions were performed with aldehydes (0.8 equiv) at −78°C or ketones (0.8 equiv) at 0°C unless otherwise indicated. [b] Yield of isolated pure product. [c] Without $PbCl_2$ (1 mol%). [d] 0.7 equiv of aldehyde was used.

Table 2. Additions of 3-substituted primary propargylic bromides to carbonyl compounds with catalytic $PbCl_2$/Al.[a]



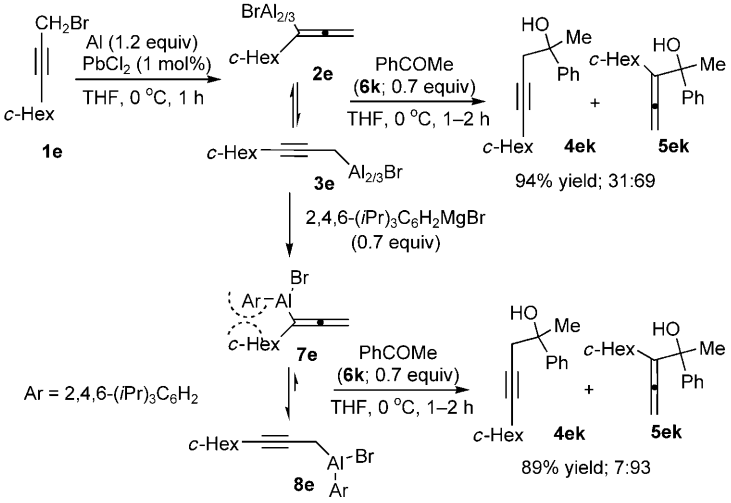
Entry	1	6	Product		Yield [%][b]
1					
	R = Hex (**1b**)	**6k**: R^1 = H	**5bk**: R^1 = H		80
2	**1b**	**6e**: R^1 = CO_2Me	**5be**: R^1 = CO_2Me		73
3	**1b**	**6l**: R^1 = CN	**5bl**: R^1 = CN		77
4					85
	1b	**6j**	**5bj**		
5					91 (14:86) 85 (6:94)[c]
	1b	**6a**	**4ba**	**5ba**	
6					
	R = TMS (**1c**)	**6k**: R^1 = H	**5ck**: R^1 = H		80
7	**1c**	**6e**: R^1 = CO_2Me	**5ce**: R^1 = CO_2Me		83
8	**1c**	**6l**: R^1 = CN	**5cl**: R^1 = CN		76
9					83
	1c	**6j**	**5cj**		
10					88
	1c	cyclohexanone **6m**	**5cm**		
11					79
	1c	**6a**	**5ca**		
12					
	R = $(CH_2)_3Cl$ (**1d**)	**6k**	**4dk**	**5dk**	93 (20:80) 91 (10:90)[c]

[a] All reactions were performed with aldehydes (0.7 equiv) at −78 °C or ketones (0.7 equiv) at 0 °C unless otherwise indicated. [b] Yield of isolated pure product. The numbers in parentheses are the ratio of **4** and **5** determined by crude ^{1}H NMR or GC analysis. [c] 2,4,6-(iPr)$_3$C$_6$H$_2$MgBr (0.7 equiv) was added. The numbers in parentheses are the ratio of **4** and **5** determined by HPLC analysis.

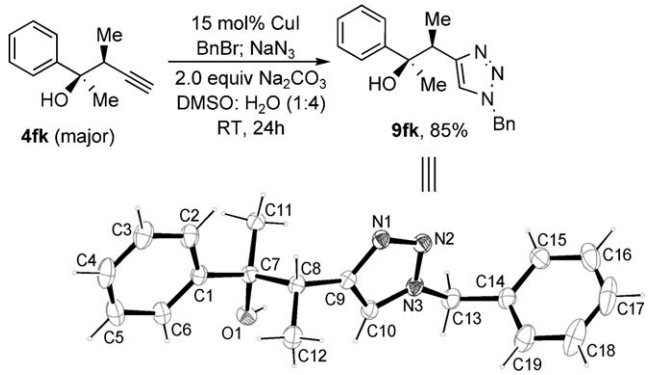
from 31:69 (94%) to 7:93 (89%). Similar changes can also be observed for the propargylic bromides **1b** and **1d** (Table 2, entries 5 and 12).

Organoaluminum reagents derived from the secondary propargylic bromides **1f** and **1g** could be prepared in a similar fashion and their addition to aldehydes and ketones were also examined under the previously optimized conditions. A complete regioselectivity is observed for all these aluminum reagents and only homopropargylic alcohols of type **4** were obtained (Table 3). The organoaluminum reagent generated from 3-bromo-1-butyne (**1f**) reacted with benzaldehyde (**6a**) furnishing homopropargyl alcohol **4fa** in 91% yield with low diastereoselectivity (Table 3, entry 1). The use of various cosolvents or additives (DME, CH_3CN, 2,6-dimethylpyridine, and diethylene glycol diethyl ether) did not improve the diastereoselectivity. Also, changing of the methyl substituent in the α position of the propargyl bromide to an isopropyl group had no influence on the diastereoselectivities (Table 3, entries 1 and 8). However, good selectivity was observed when cyclohexanecarboxaldehyde (**6d**) was used. In this case, the *anti* adduct is the major isomer (Table 3, entry 2).[16] Note that the addition of the allenylaluminum reagents **2f** and **2g** to various ketones always proceeds with high yields (85–92%) and diastereoselectivities (up to 97:3; Table 3, entries 3, 4, 6, and 9). There are very few reports in the literature on the preparation of tertiary homopropargylic alcohols with such high diastereoselectivites.[17]

To determine the relative stereochemistry of these tertiary alcohols, the major isomer **4fk** was successfully converted to the 1,4-disubstituted 1,2,3-triazole **9fk** via a copper(I)-catalyzed three-component [3+2] cycloaddition reaction in 85% yield.[18] The relative stereochemistry of compound **9fk** was determined by its X-ray crystal structure (Scheme 3). This indicated that the reaction of the allenylaluminum spe-



Scheme 2. Postulated reaction pathway.



Scheme 3. Determination of the relative stereochemistry of the alcohol **4fk**.

cies **2f** with acetophenone (**6k**) proceeded with *syn* selectivity. This *syn* selectivity may result from the transition state **11** depicted in Figure 1. This cyclic transition state is favored compared to the alternative cyclic transition state **12** for steric reasons. The preferential formation of *syn*-**4fk** over *anti*-**4fk** is consistent with the rule proposed by Seebach and Golinski.[19] Furthermore, the major isomer **4fh** was also converted successfully into the 1,4-disubstituted 1,2,3-triazole **9fh** in 90% yield, which was further converted to the

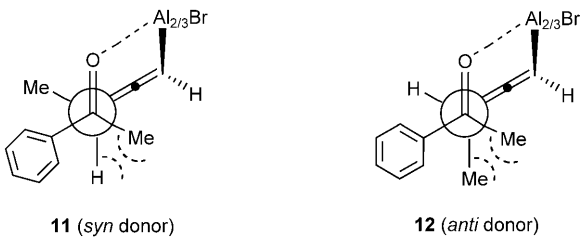
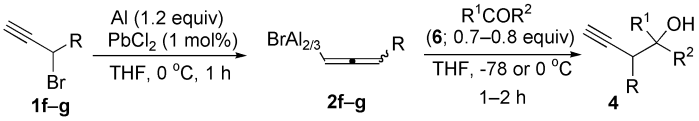
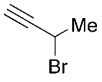
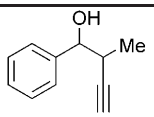
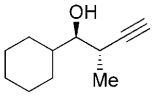
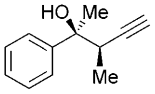
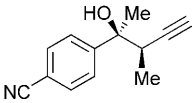
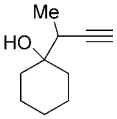
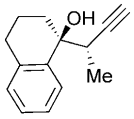
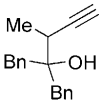
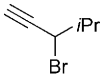
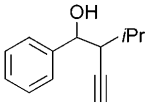
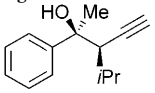


Figure 1. Possible transition state for addition of the allenylaluminum species **2f** to acetophenone (**6k**).

Table 3. Reactions of terminal secondary propargylic bromides with carbonyl compounds with catalytic $PbCl_2$/Al.[a]

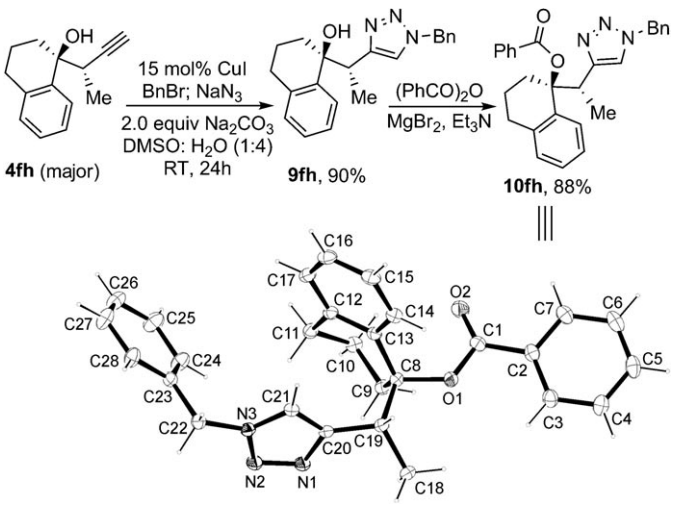


Entry	1	6	Product	Yield [%][b]
1				91 (56:44)
	1f	PhCHO **6a**	**4fa**	
2				91 (88:12)
	1f	c-C_6H_{11}CHO **6d**	**4fd**	
3				85 (89:11)
	1f	PhCOMe **6k**	**4fk**	
4				87 (88:12)
	1f	4-NCC_6H_4COMe **6l**	**4fl**	
5				87
	1f	cyclohexanone **6m**	**4fm**	
6				
	1f	α-tetralone **6h**	**4fh**	90 (94:6)
7				
	1f	1,3-diphenylpropan-2-one **6j**	**4fj**	92
8				90 (56:44)
	1g	PhCHO **6a**	**4ga**	
9				92 (97:3)
	1g	PhCOMe **6k**	**4gk**	

[a] All reactions were performed with aldehydes (0.8 equiv) at −78 °C or ketones (0.7 equiv) at 0 °C unless otherwise indicated. [b] Yield of isolated pure product. The numbers in parentheses are the ratios of diastereoselectivies determined by crude ^{1}H NMR analysis.

corresponding benzoyl ester **10fh** in 88% isolated yield by Vedejs' method,[20] the stereochemistry of which was also determined by X-ray analysis (Scheme 4).

Remarkably, by using the 3-substituted propargylic bromides **1h–j** as precursors, only the homopropargylic alcohols of type **4** as single regioisomers in 68–98% yield (Table 4)



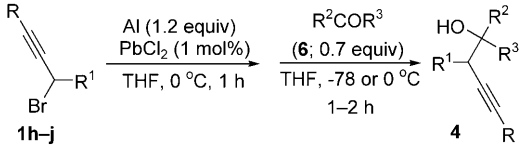
Scheme 4. Determination of the relative stereochemistry of the alcohol **4fh**.

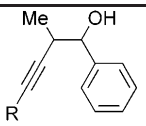
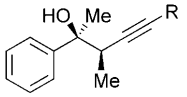
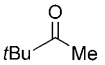
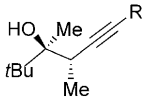
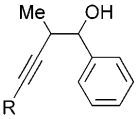
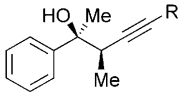
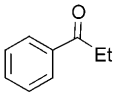
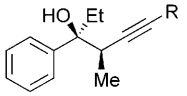
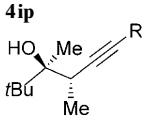
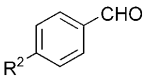
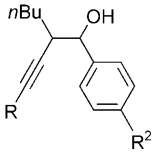
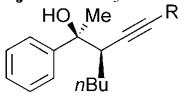
were obtained. Propargylic bromide **1i** (R = $(CH_2)_2$OMe; R^1 = Me) that has a methoxy group furnished better yields than the propargylic bromide **1h** (R = *n*Bu; R^1 = Me) under the same conditions (Table 4, entries 1–3 versus entries 4, 5, and 7). We propose that the oxygen atom of the methoxy group stabilized the allenylaluminum species. These allenylaluminum reagents reacted with benzaldehyde (**6a**) affording the corresponding homopropargylic acohols **4ha**, **4ia**, and **4ja** in 76, 90, and 96% yields, respectively, but with low diastereoselectivities (Table 4, entries 1, 4, and 8). No improvement was obtained by using the corresponding organozinc reagent prepared from **1i** (Table 4, entry 4). Much to our delight, excellent diastereoselectivities were also obtained for the addition of these allenylaluminum species to various ketones (Table 4, entries 2–3, 5–7, and 11).[21] It is interesting to note that *syn* selectivity is preferred for aromatic ketones, whereas *anti* selectivity is predominant for a sterically hindered aliphatic ketone such as *t*BuCOMe (Table 4, entries 3 and 7).[22]

Conclusion

In summary, we have reported a new and efficient preparation of allenic- and propargylic aluminum reagents under mild conditions. These organoaluminum species react with carbonyl compounds (aldehydes or ketones) to give the homopropargylic or allenic alcohols in good to excellent yields and in several cases with high diastereoselectivity. Various functional groups such as ester, cyanide, primary amino groups, and the relatively acidic methylene group are tolerated in this reaction.

Table 4. Reactions of internal secondary propargylic bromides with carbonyl compounds with catalytic $PbCl_2$/Al.[a]



Entry	1	6	Product	Yield [%][b]
1				
	R = *n*Bu R^1 = Me (**1h**)	**6a**	**4ha**	76 (60:40)
2				73 (94:6)
	1h	**6k**	**4hk**	
3				68 (99:1)[d]
	1h	**6o**	**4ho**	
4				90 (55:45) 88 (50:50)[c]
	R = $(CH_2)_2$OMe R^1 = Me (**1i**)	**6a**	**4ia**	
5				93 (92:8)
	1i	**6k**	**4ik**	
6				98 (91:9)
	1i	**6p**	**4ip**	
7				86 (99:1)[d]
	1i	**6o**	**4io**	
8				
	R = $(CH_2)_2$OMe R^1 = *n*Bu (**1j**)	**6a**: R^2 = H	**4ja**: R^2 = H	96 (55:45)
9	**1j**	**6q**: R^2 = OMe	**4jq**: R^2 = OMe	98 (54:46)
10	**1j**	**6r**: R^2 = CF_3	**4jr**: R^2 = CF_3	90 (31:69)
11				88 (92:8)
	1j	**6k**	**4jk**	

[a] All reactions were performed with aldehydes (0.7 equiv) at −78 °C or ketones (0.7 equiv) at 0 °C unless otherwise noted. [b] Yield of isolated pure product. The numbers in parentheses are the ratios of diastereoselectivies determined by crude ^{1}H NMR or GC analysis. [c] The organozinc reagent was used. [d] The relative stereochemistry of the alcohol **4ho** and **4io** were determined by NOESY spectroscopy.

Experimental Section

General methods: All reactions were carried out under a nitrogen atmosphere in flame-dried glassware by using Schlenk techniques. Syringes were purged with nitrogen prior to use. THF was continuously heated to reflux and was freshly distilled from sodium benzophenone ketyl under nitrogen. Melting points are uncorrected and were measured on a Büchi B.540 apparatus. ^{1}H and ^{13}C NMR spectra were recorded on a Bruker AC 300 or WH 400 instrument. Chemical shifts are given in ppm relative to the residual solvent peak ([D_1]chloroform: 7.26 ppm/77.0 ppm; [D_6]benzene 7.16 ppm/128.0 ppm). IR spectra were recorded on a Nicolet 510 FT-IR or a Perkin–Elmer 281 IR spectrometer. Mass spectra were recorded on a Finnigan MAT 95Q Finnigan MAT90 instrument. Column chromatography purification was performed on Merck silica gel 60 (230–400 mesh ASTM).

General procedure for the preparation of the organoaluminum reagent: A dry, argon-flushed Schlenk flask equipped with a magnetic stirrer and a rubber septum was charged with anhydrous $PbCl_2$ (5.6 mg, 0.02 mmol, 1 mol%) and the flask was dried with a heating gun for 3 min under high vacuum. To this flask was added aluminum powder (65 mg, 2.4 mmol) and the flask was evacuated and refilled with argon. After the addition of freshly distilled THF (2 mL), propargyl bromide (2.0 mmol) was added in one portion when the solution was cooled to 0 °C. After stirring for 1 h at this temperature, the reaction mixture was then cannulated to a new Schlenk flask for the reaction with an electrophile at −78 °C or 0 °C.

General procedure for addition reactions: A dry Schlenk flask equipped with a magnetic stirrer and a rubber septum was charged with the corresponding electrophile (1.4 or 1.6 mmol, 0.7 or 0.8 equiv). The flask was thoroughly flushed with argon, and freshly distilled THF (0.5 mL) was added to it through the rubber septum. The resultant mixture was stirred at −78 °C or 0 °C for 2 min before the corresponding aluminum reagent was slowly cannulated into the flask and the mixture was stirred at −78 °C or 0 °C from 1 h to 2 h. Once the GC analysis of a standard aliquot had indicated the consumption of the electrophile, the reactions were quenched with saturated aqueous NH_4Cl. The mixture was extracted with EtOAc (3×20 mL), washed with saturated aqueous $NaHCO_3$, water, and saturated NaCl solution. The combined organic layers were dried over Na_2SO_4 and the solvents were removed under reduced pressure to furnish the crude product, which was further purified by column chromatography (silica gel) to obtain an analytically pure sample.

X-ray crystallographic analysis: CCDC-766013 (**9 fk**), 766014 (**10 fh**), and 766015 (**10 ik**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Acknowledgements

L.-N.G and H.G. thank the Humboldt Foundation for financial support. We thank the Fonds der Chemischen Industrie, the European Research Council (ERC), Chemetall GmbH (Frankfurt), and BASF AG (Ludwigshafen) for financial support.

[1] B. M. Trost, *Science* **1991**, *254*, 1471–1477.
[2] R. D. Rieke, M. V. Hanson, *Tetrahedron* **1997**, *53*, 1925–1956, and references therein.
[3] a) A. Krasovskiy, V. Malakhov, A. Gavryushin, P. Knochel, *Angew. Chem.* **2006**, *118*, 6186–6190; *Angew. Chem. Int. Ed.* **2006**, *45*, 6040–6044; b) N. Boudet, S. Sase, P. Sinha, C.-Y. Liu, A. Krasovskiy, P. Knochel, *J. Am. Chem. Soc.* **2007**, *129*, 12358–12359.
[4] a) F. M. Piller, P. Appukkuttan, A. Gavryushin, M. Helm, P. Knochel, *Angew. Chem.* **2008**, *120*, 6907–6911; *Angew. Chem. Int. Ed.* **2008**, *47*, 6802–6806; b) A. Metzger, F. M. Piller, P. Knochel, *Chem. Commun.* **2008**, 5824–5826.
[5] a) Y.-H. Chen, P. Knochel, *Angew. Chem.* **2008**, *120*, 7760–7763; *Angew. Chem. Int. Ed.* **2008**, *47*, 7648–7651; b) Y.-H. Chen, M. Sun, P. Knochel, *Angew. Chem.* **2009**, *121*, 2270–2273; *Angew. Chem. Int. Ed.* **2009**, *48*, 2236–2239.
[6] K. Takai, T. Ueda, T. Hayashi, T. Moriwake, *Tetrahedron Lett.* **1996**, *37*, 7049–7052.
[7] T. Blümke, Y.-H. Chen, Z. Peng, P. Knochel, *Nat. Chem. Biol.* **2010**, *2*, 313–318.
[8] The organoaluminum reagents are equimolar mixtures of $RAlBr_2$ and R_2AlBr, which is summarized by $RAl_{2/3}Br$.
[9] a) R. G. Daniels, L. A. Paquette, *Tetrahedron Lett.* **1981**, *22*, 1579–1582; b) M. J. Lin, T. P. Loh, *J. Am. Chem. Soc.* **2003**, *125*, 13042–13043; c) W. Miao, L. W. Chung, Y.-D. Wu, T. H. Chan, *J. Am. Chem. Soc.* **2004**, *126*, 13326–13334.
[10] a) M. Gaudemar, *Ann. Chim. (Cachan Fr.)* **1956**, *1*, 161–213; b) M. Gaudemar, *Bull. Soc. Chim. Fr.* **1958**, 1475–1477.
[11] K. Eiter, H. Oediger, *Justus Liebigs Ann.* **1965**, *682*, 62–70.
[12] a) F. Sondheimer, Y. Amiel, Y. Gaoni, *J. Am. Chem. Soc.* **1962**, *84*, 270–274; b) E. Crundwell, A. L. Cripps, *J. Med. Chem.* **1972**, *15*, 754–756; c) G. Picotin, P. Miginiac, *J. Org. Chem.* **1985**, *50*, 1299–1301; d) L. Leboutet, G. C. L. Miginiac, *J. Organomet. Chem.* **1991**, *420*, 155–161.
[13] For general activation of Al powder, see: S. Saito, *Science of Synthesis (Houben–Weyl), Vol. 7* (Ed.: H. Yamamoto), **2004**, pp. 5–14.
[14] Aluminum powder has been previously activated by $SnCl_2$, $PbBr_2$, $BiCl_3$, $InCl_3$, and $CoCl_2$ for insertion to allyl bromide and chloride, see: a) K. Uneyama, N. Kamaki, A. Moriya, S. Torii, *J. Org. Chem.* **1985**, *50*, 5396–5399; b) H. Tanaka, S. Yamashita, T. Hamatani, Y. Ikemoto, S. Torii, *Synth. Commun.* **1987**, *17*, 789–794; c) M. Wada, H. Ohki, K.-y. Akiba, *Bull. Chem. Soc. Jpn.* **1990**, *63*, 1738–1747; d) S. Araki, S.-J. Jin, Y. Idou, Y. Butsugan, *Bull. Chem. Soc. Jpn.* **1992**, *65*, 1736–1738; e) R. H. Khan, T. S. R. Prasada Rao, *J. Chem. Res. Synop.* **1998**, 202–203.
[15] For selected examples, see: a) H. Yamamoto in *Comprehensive Organic Synthesis* (Eds.: B. M. Trost, I. Fleming), Pergamon, Oxford, **1991**; b) S. Kobayashi, K. Nishio, *J. Am. Chem. Soc.* **1995**, *117*, 6392–6393; c) M. B. Isaac, T.-H. Chan, *J. Chem. Soc. Chem. Commun.* **1995**, 1003–1004; d) X.-H. Yi, Y. Meng, X.-G. Hua, C.-J. Li, *J. Org. Chem.* **1998**, *63*, 7472–7480; e) Z. Li, Y. Jia, J. Zhou, *Synth. Commun.* **2000**, *30*, 2515–2524; f) T. P. Loh, M. J. Lin, K. L. Tan, *Tetrahedron Lett.* **2003**, *44*, 507–509; g) A. S.-Y. Lee, S.-F. Chu, Y.-T. Chang, S.-H. Wang, *Tetrahedron Lett.* **2004**, *45*, 1551–1553; h) P. H. Lee, H. Kim, K. Lee, *Adv. Synth. Catal.* **2005**, *347*, 1219–1222; i) J. M. Huang, H. C. Luo, Z. X. Chen, G. C. Yang, T. P. Loh, *Eur. J. Org. Chem.* **2008**, 295–298; j) X. Ma, J.-X. Wang, S. Li, K.-H. Wang, D. Huang, *Tetrahedron* **2009**, *65*, 8683–8689.
[16] J. A. Marshall, N. D. Adams, *J. Org. Chem.* **1998**, *63*, 3812–3813.
[17] a) T. Takeda, M. Ando, T. Sugita, A. Tsubouchi, *Org. Lett.* **2007**, *9*, 2875–2878; b) J. Tummatorn, G. B. Dudley, *J. Am. Chem. Soc.* **2008**, *130*, 5050–5051.
[18] Y.-B. Zhao, Z.-Y. Yan, Y.-M. Liang, *Tetrahedron Lett.* **2006**, *47*, 1545–1549.
[19] a) Y. Matsumoto, M. Naito, Y. Uozumi, T. Hayashi, *J. Chem. Soc. Chem. Commun.* **1993**, 1468–1469; b) D. Seebach, J. Golinski, *Helv. Chim. Acta* **1981**, *64*, 1413–1423.
[20] E. Vedejs, O. Daugulis, *J. Org. Chem.* **1996**, *61*, 5702–5703.
[21] The relative stereochemistry of **4 ik** was also determined by its corresponding ester (see the Supporting Information).
[22] a) G. Zweifel, G. Hahn, *J. Org. Chem.* **1984**, *49*, 4565–4567; b) Y. Matsumoto, *J. Org. Chem.* **1986**, *51*, 886–891.

Received: February 28, 2010
Published online: June 22, 2010

