DOI: 10.1002/ange.201002751

Asymmetric Catalysis

Asymmetric Nozaki–Hiyama Propargylation of Aldehydes: Enhancement of Enantioselectivity by Cobalt Co-Catalysis**

*Dmitry L. Usanov and Hisashi Yamamoto**

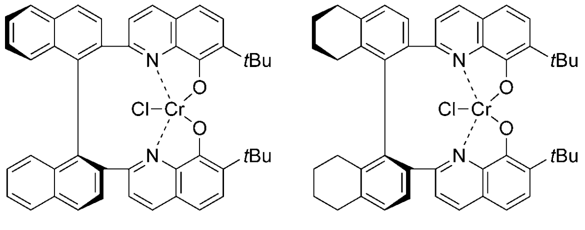
The addition of organochromium reagents to carbonyl compounds, pioneered by Nozaki and Hiyama in late 1970s, has been an important tool in contemporary organic synthesis because of a number of unique features, such as mild reaction conditions, high chemoselectivity, and compatibility with a wide range of functional groups.[1,2] However, the necessity to use superstoichiometric amounts of toxic chromium reagents was among the major drawbacks. In 1996 Fürstner and Shi reported the first example of this reaction being catalytic in chromium, which turned Nozaki–Hiyama chemistry into a more environmentally benign methodology.[3] This seminal report gave rise to a number of asymmetric applications of catalytic Nozaki–Hiyama (NH) processes.[4]

Chiral homopropargyl alcohols are among the products which are potentially accessible using NH methodology. Most of the asymmetric methods that provide access to these compounds involve the use of chiral allenyl reagents.[5] A number of enantioselective procedures involving achiral allenyl species have also been reported.[6] A catalytic enantioselective NH propargylation reaction is thus an advantageous alternative to these approaches owing to the ready availability of propargyl halides as the propargyl moiety sources.[7]

The first examples of enantioselective NH propargylation were reported by Cozzi, Umani-Ronchi, and co-workers and involved the use of chromium complexes derived from chiral salen ligands (10 mol %, up to 56 % *ee*).[8] In 2004, Inoue and Nakada described a superior procedure involving a tridentate carbazole ligand (10 mol %), which furnished most of the products with 51–82 % *ee* (the catalyst showed exceptional enantiocontrol for pivalaldehyde, 98 % *ee*).[9] Recently Kishi and co-workers reported the implementation of NH propargylation into the total synthesis of halichondrin.[10] A number of homopropargyl alcohols were obtained in 55–94 % yield and 46–93 % *ee* using chiral sulfonamide ligands; the scope of the study was mostly focused on aliphatic substrates.

However, the existing methods involve relatively high catalyst loadings (10 mol %); as such, the development of a protocol employing lesser amounts of chromium would be highly desirable. In addition, room for improvement with respect to enantioselectivity still remains for a range of substrates. For instance, for aromatic aldehydes, enantioselectivities exceeding 80 % *ee* have not been achieved using NH methodology.

Recently, our group developed a tethered bis(8-quinolinato) (TBOx) chromium complex **1**,[11] which was successfully used as a highly stereoselective catalyst for asymmetric pinacol coupling,[12] asymmetric NH allylation[13] and allenylation[14] of aldehydes, as well as for the asymmetric synthesis of 1,3-butadien-2-ylcarbinols (Scheme 1).[15] In light of these applications, we envisioned that **1** could potentially be used as a catalyst in asymmetric NH propargylation reactions.



1 **2**

Scheme 1. TBOx derivatives used in Nozaki–Hiyama chemistry.

We started our studies using the conditions previously used for other NH processes:[12,13] 0.5 mmol of benzaldehyde, 3 equivalents of manganese, 1 equivalent of TESCl, and 1.5 equivalents of propargyl bromide were mixed in 2 mL of solvent in the presence of 3 mol % of **1** for 40 hours at room temperature. A solvent screen demonstrated that only a limited number of solvents were suitable for the propargylation reaction; tetrahydrofuran appeared to be superior to the majority of other common solvents (60 % conversion after 40 h, 67 % *ee*). Interestingly, 2-methyltetrahydrofuran showed a slight increase of enantioselectivity compared to tetrahydrofuran (72 % *ee*). However, the latter was used as a solvent for the further preliminary screening experiments for reasons of convenience.

Tuning the size of the silyl group of the product scavenger led to a bell-shaped dependence: increasing the size first resulted in an enhancement of the enantioselectivity (Table 1, entries 1–3); however, bulkier silyl chlorides (Table 1, entries 4 and 5) furnished the product with inferior *ee* values. An inverse dependence of the reactivity on the size of the scavenger was observed over the tested range. These

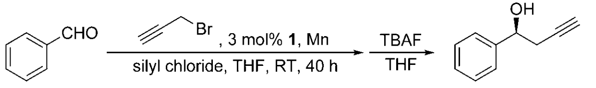
---

[*] D. L. Usanov, Prof. Dr. H. Yamamoto
Department of Chemistry, The University of Chicago
5735 South Ellis Avenue, Chicago, IL 60637 (USA)
Fax: (+1) 773-702-0805
E-mail: yamamoto@uchicago.edu
Homepage: http://yamamotogroup.uchicago.edu/

[**] This work was made possible by the generous support of the NSF (CHE-0717618). We thank Dr. Guoyao Xia and Dr. Marina Naodovic for their involvement in the preliminary stage of this project.

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/anie.201002751.

Table 1: The effect of silyl chloride on the catalytic asymmetric Nozaki–Hiyama propargylation of benzaldehyde.



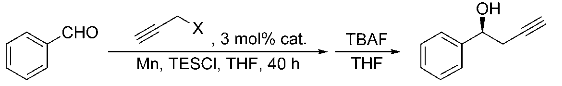
Entry	Silyl chloride	Conversion [%][a]	*ee* [%][b]
1	TMSCl	79	33
2	TESCl	68	67
3	*n*-Pr_3SiCl	45	70
4	TBDMSCl	26	62
5	TTMSSCl	18	61

[a] Determined by ^1H NMR analysis of the crude material after the workup. [b] Determined by HPLC on a chiral OD-H column. TMSCl = trimethylsilyl chloride, TES = triethylsilyl chloride, TBDMSCl = *tert*-butyldimethylsilyl chloride, TTMSS = tris(trimethylsilyl)silyl chloride.

observations led to the conclusion that the silyl chloride is directly involved in the stereo-determining step, possibly via Lewis acid activation of the substrate.

The reaction temperature appeared to have a dramatic impact on the catalysis efficiency. Thus, at 0 °C, almost no reactivity was observed along with significant loss of enantioselectivity (Table 2, entry 1). In contrast, carrying out the reaction at 40 °C (Table 2, entry 3) resulted in enhanced enantiocontrol and higher conversion.

Table 2: Screening of temperature and propargyl source in catalytic asymmetric Nozaki–Hiyama propargylation of benzaldehyde.



Entry	Catalyst	X	*T* [°C]	Conversion [%][a]	*ee* [%][b]
1	**1**	Br	0	5	14
2	**1**	Br	RT	68	67
3	**1**	Br	40	> 95	73
4[c]	**1**	Cl	RT	10	74
5[c]	**1**	Cl	40	27	79
6	**1**	I	RT	> 95	28
7	–	Cl	RT	–	–
8	–	Br	RT	12	–
9	**2**	Br	RT	94	80

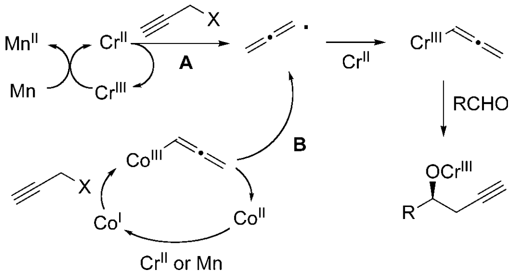
[a] Determined by ^1H NMR analysis of the crude material after the work-up. [b] Determined by HPLC on a chiral OD-H column. [c] The pinacol coupling product was formed in appreciable extent.

We then tested the influence of the type of propargyl halide on the reaction outcome: the reactivity of the halide increased according to the series Cl < Br < I, accompanied by a decrease of the enantioselectivity (Table 2, entries 2, 4, and 6). Based on this observation, together with temperature studies, we hypothesized that propargyl halides can react with manganese to form organomanganese species, which can furnish the homopropargyl alcohol with compromised enantiocontrol. Even though oxidative insertion of manganese to organic halides is considered to be largely unknown,[3b] a number of reports indicate that this pathway is feasible for the most-reactive halides.[16] The rate of formation of organomanganese species would increase in the order Cl < Br < I, which is in compliance with the observed stereoselectivity profile. Background experiments confirmed this assumption (Table 2, entries 7 and 8).

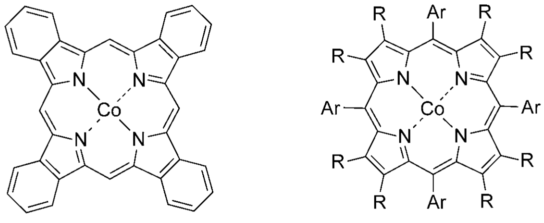
It should be noted that the previously reported reactivities and enantioselectivities appeared to be different from those obtained subsequently;[15] numerous experiments with different batches of TBOx CrCl were consistent with the result shown in Table 1, entry 2. The reasons for this phenomenon are currently under investigation.

We considered an idea to prepare a partially reduced H_8-TBOx ligand, which gives rise to complex **2**, in order to test whether the introduction of aliphatic moieties can exert any impact on the reactivity and stereocontrol of the catalysis. This type of modification of the TBOx backbone has not been tested thus far.[11–15] To our delight, complex **2** furnished the homopropargyl alcohol with appreciably enhanced enantioselectivity of 80 % *ee* (Table 2, entry 9). In order to further enhance the enantiopurity of the product, we focused our studies on the suppression of the background process.

In the conventional NH catalytic cycle, the electrons are supposedly transferred from the chromium(II) species to the propargyl halide (Scheme 2, **A**). In 1989 Takai and Utimoto reported the chromium-mediated preparation of secondary alcohols from aldehydes and alkyl halides catalyzed by vitamin B_{12} or cobalt phthalocyanine **3**.[18] The key point of the procedure was the formation of alkyl radicals from the $Co^I/Co^{II}/Co^{III}$ cycle, which were then captured by chromium species able to attack the carbonyl group. The formation of stabilized radicals from the corresponding halides by means of cobalt(I) complexes is well-known.[19] Addition of cobalt phthalocyanine **3** (Scheme 3) was also reported to be



Scheme 2. Putative mechanism for the Nozaki–Hiyama propargylation: standard (A) and co-catalyzed (B) routes.



3

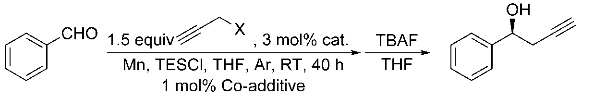
4, R = H, Ar = *p*-$MeOC_6H_4$
5, R = Et, Ar = H

Scheme 3. Cobalt additives used in asymmetric Nozaki–Hiyama propargylation.

beneficial for the reaction rate for some of the NH processes.[20] Inspired by those reports, we assumed that cobalt co-catalysis was able to accelerate the initial radical formation step and thus could lead to enhancement of the enantioselectivity of the TBOx CrCl-mediated asymmetric NH propargylation (Scheme 2, **B**).

The use of $[(Ph_3P)_3Co^ICl]$ or $[(Ph_3P)_2Co^{II}Cl_2]$ as additives did result in an appreciable acceleration of the process; however, a substantial drop in enantioselectivity was observed; the effect was even more profound for cobalt phthalocyanine **3** (Table 3). These experiments indicated that cobalt complexes were able to transfer the propargyl moiety directly onto the substrate; this suggestion was confirmed by blank experiments carried out in the absence of the TBOx chromium complex.[21] In an attempt to eliminate this pathway, we tested commercially available tetraarylporphine complex **4**. Anisyl groups, orthogonal to the porphine ring plane, were expected to provide steric hindrance for the direct attack on the substrate. To our delight, in addition to increased reactivity, we observed enhancement of enantioselectivity with respect to the process catalyzed solely by **1** and **2** (Table 3, entries 4 and 5). 2-Methyltetrahydrofuran also appeared to be superior to tetrahydrofuran under the conditions of cobalt co-catalysis (Table 3, entry 7). When propargyl chloride was employed under the modified conditions, the same level of enantiocontrol was observed (Table 3, entries 6 and 8 versus 7).

Table 3: Screening of cobalt additives in Nozaki–Hiyama propargylation of benzaldehyde.



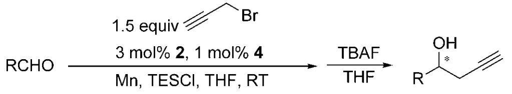
Entry	Cat.	X	Additive	Conversion [%][a]	*ee* [%][b]
1	**1**	Br	$[(PPh_3)_3Co^ICl]$	>95	45
2	**1**	Br	$[(PPh_3)_2Co^{II}Cl_2]$	>95	59
3	**1**	Br	**3**	>95	10
4	**1**	Br	**4**	81	78
5	**2**	Br	**4**	>95	85
6	**2**	Cl	**4**	39	91
7[d,e]	**2**	Br	**4**	>95	91
8[c,d]	**2**	Cl	**4**	36	90
9	**2**	Br	**5**	>95	92
10[d,e]	**2**	Br	**5**	>95	90

[a] Determined by ^{1}H NMR analysis of the crude material after the workup. [b] Determined by HPLC on a chiral OD-H type column. [c] 3 mol% of the additive was used. [d] 2-Methyltetrahydrofuran was used as a solvent. [e] $CaCO_3$ (20 mol%) was used as an additive.[17]

Interestingly, when the less sterically hindered complex **5** was used as an additive, enhancement of the enantioselectivity was also observed to a comparable extent with that provided by complex **4** (Table 3, entries 9 and 10).[22] Thus, the background reaction catalyzed by **3** was faster than the one mediated by porphine complexes, presumably owing to electronic effects rather than steric.[21]

A range of various aldehydes were tested in order to study the scope and limitations of the developed procedure (Table 4). Generally, reactions run in 2-methyltetrahydrofuran demonstrated higher enantioselectivities and the products were isolated in somewhat lower yields compared to the reactions in tetrahydrofuran.[17] Aromatic aldehydes showed superior reactivity and stereoselectivity profiles with respect to aliphatic substrates. This procedure could also be applied to some of α,β-unsaturated and heteroaromatic aldehydes to give homopropargyl alcohols with enantioselectivities of 84–93% *ee*.

Table 4: Asymmetric Nozaki–Hiyama propargylation catalyzed by **2**.



Entry	R	*t* [h]	Yield [%][a]	*ee* [%][b]
1[c]	Ph	40	75	91
2	*p*-MeO-C_6H_4	48	83	89
3	*o*-F-C_6H_4	90	63	78
4[c]		48	40	88
5	*p*-Cl-C_6H_4	150	73	88
6[c]		100	54	92
7	1-naphthyl	100	78	84
8[c]		60	81	86
9	2-naphthyl	120	79	75
10[c]		78	64	89
11	(*E*)-PhCH=CH	90	40	92
12	(*E*)-PhCH=C(Me)	60[d]	91	84
13[c]		60[d]	86	84
14	2-furanyl	25	69	93
15[c]		35	51	92
16	2-thienyl	60[d]	74	80
17[c]		60[d]	70	87
18	$PhCH_2CH_2$	90	42	34
19	cyclohexyl	90	37	29[e]

[a] Yield of isolated product after purification on silica gel. [b] Determined by HPLC on a chiral column. [c] Reactions were carried out in 2-methyltetrahydrofuran in the presence of 20 mol% of $CaCO_3$.[17] [d] The reaction time was not optimized. [e] Determined by ^{1}H NMR analysis after esterification with (*R*)-MTPACl.

In summary, we have developed a highly enantioselective catalytic system for the Nozaki–Hiyama propargylation of aldehydes employing lowered catalyst loading (3 mol%); enantioselectivities of 84–93% *ee*, hitherto unapproachable for aromatic, heteroaromatic, and α,β-unsaturated aldehydes using NH chemistry, were obtained for a range of substrates. A beneficial influence of the partially reduced binaphthyl moiety on enantiocontrol was observed, thus resulting in the development of a new type of H_8-TBOx ligand. The important role of the background reaction presumably caused by organomanganese compounds formed in situ was demonstrated; the issue was efficiently overcome by introduction of an additional cobalt-mediated catalytic cycle, which resulted in enhancement of enantioselectivity. Commercially available porphine complexes, hitherto never used in NH processes, were found to serve as unique auxiliaries, whereas conventional cobalt additives were shown to be ineffective.

We believe that the use of cobalt porphine co-catalysts can be beneficial for other asymmetric NH-type methods hitherto poorly explored, presumably owing to low stereoselectivity levels caused by background reactions. Studies in these directions are currently undergoing in our group.

Experimental Section

Representative procedure for asymmetric propargylation: a flame-dried argon-filled test tube sealed with a sleeve stopper was charged with **4** (4 mg, 0.005 mmol), (H_8-TBOx)CrCl **2** (12 mg, 0.015 mmol), manganese powder (81 mg, 1.47 mmol), and $CaCO_3$ (10 mg, 0.01 mmol). 2-Methyltetrahydrofuran (2 mL) was then added, and the mixture was left stirring at room temperature for 10 minutes. Then propargyl bromide (55 µL, 0.73 mmol) was added dropwise followed by benzaldehyde (50 µL, 0.49 mmol) and chlorotriethylsilane (83 µL, 0.49 mmol). The mixture was stirred vigorously at room temperature (22 °C) for 40 hours. The reaction mixture was then quenched with aqueous saturated $NaHCO_3$ solution and extracted with dichloromethane. The extracts were dried over anhydrous Na_2SO_4, and concentrated under vacuum. 1M TBAF solution in tetrahydrofuran was then added (1 mL, 1 mmol), and the mixture was left at room temperature for 1 hour. It was then diluted with dichloromethane and washed with brine. The aqueous layer was back extracted with dichloromethane. The combined organic phases were dried over anhydrous Na_2SO_4, and the solvent was evaporated. Column chromatography of the resulting residue on silica gel in 1:10 ethyl acetate/hexanes solvent system afforded the homopropargyl alcohol (53 mg, 75 % yield, 91 % *ee*).

Received: May 6, 2010
Revised: June 26, 2010

Keywords: asymmetric catalysis · chromium · cobalt · homopropargyl alcohols · propargylation

---

[1] a) Y. Okude, S. Hirano, T. Hiyama, H. Nozaki, *J. Am. Chem. Soc.* **1977**, *99*, 3179–3181; b) T. Hiyama, K. Kimura, H. Nozaki, *Tetrahedron Lett.* **1981**, *22*, 1037–1040; c) T. Hiyama, Y. Okude, K. Kimura, H. Nozaki, *Bull. Chem. Soc. Jpn.* **1982**, *55*, 561–568; d) K. Takai, K. Kimura, T. Kuroda, T. Hiyama, H. Nozaki, *Tetrahedron Lett.* **1983**, *24*, 5281–5284; e) K. Takai, T. Kuroda, S. Nakatsukasa, K. Oshima, H. Nozaki, *Tetrahedron Lett.* **1985**, *26*, 5585–5588.

[2] For recent reviews, see: a) A. Fürstner, *Chem. Rev.* **1999**, *99*, 991–1045; b) L. A. Wessjohann, G. Scheid, *Synthesis* **1999**, 1–36; c) K. Takai, H. Nozaki, *Proc. Jpn. Acad. Ser. B* **2000**, *76*, 123–131.

[3] a) A. Fürstner, N. Shi, *J. Am. Chem. Soc.* **1996**, *118*, 2533–2534; b) A. Fürstner, N. Shi, *J. Am. Chem. Soc.* **1996**, *118*, 12349–12357.

[4] For reviews focused on asymmetric protocols, see: a) G. C. Hargaden, P. J. Guiry, *Adv. Synth. Catal.* **2007**, *349*, 2407–2424; b) M. Inoue, T. Suzuki, A. Kinoshita, M. Nakada, *Chem. Rec.* **2008**, *8*, 169–181.

[5] For reviews, see: a) S. Denmark, J. Fu, *Chem. Rev.* **2003**, *103*, 2763–2794; b) J. A. Marshall, *J. Org. Chem.* **2007**, *72*, 8153–8166.

[6] a) N. Minowa, T. Mukaiyama, *Bull. Chem. Soc. Jpn.* **1987**, *60*, 3697–3704; b) E. J. Corey, C.-M. Yu, D.-H. Lee, *J. Am. Chem. Soc.* **1990**, *112*, 878–879; c) T. P. Loh, M.-J. Lin, K.-L. Tan, *Tetrahedron Lett.* **2003**, *44*, 507–509; d) G. E. Keck, D. Krishnamurthy, X. Chen, *Tetrahedron Lett.* **1994**, *35*, 8323–8324; e) C.-M. Yu, H.-S. Choi, S.-K. Yoon, W.-H. Jung, *Synlett* **1997**, 889–890; f) C.-M. Yu, S.-K. Yoon, H.-S. Choi, K. Baek, *Chem. Commun.* **1997**, 763–764; g) C.-M. Yu, S.-K. Yoon, K. Baek, J.-Y. Lee, *Angew. Chem.* **1998**, *110*, 2504–2506; *Angew. Chem. Int. Ed.* **1998**, *37*, 2392–2395; h) K. Iseki, Y. Kuroki, Y. Kobayashi, *Tetrahedron: Asymmetry* **1998**, *9*, 2889–2894; i) S. E. Denmark, T. Wynn, *J. Am. Chem. Soc.* **2001**, *123*, 6199–6200; j) D. A. Evans, Z. K. Sweeney, T. Rovis, J. S. Tedrow, *J. Am. Chem. Soc.* **2001**, *123*, 12095–12096; k) M. Nakajima, M. Saito, S. Hashimoto, *Tetrahedron: Asymmetry* **2002**, *13*, 2449–2452; l) S. Konishi, H. Hanawa, K. Maruoka, *Tetrahedron: Asymmetry* **2003**, *14*, 1603–1605; m) H. Hanawa, D. Uraguchi, S. Konishi, T. Hashimoto, K. Maruoka, *Chem. Eur. J.* **2003**, *9*, 4405–4413; n) C.-M. Yu, J.-M. Kim, M.-S. Shin, D. Cho, *Tetrahedron Lett.* **2003**, *44*, 5487–5490.

[7] For the preparation of homopropargyl alcohols directly from propargyl halides, see: a) T.-P. Loh, M.-J. Lin, K.-L. Tan, *Tetrahedron Lett.* **2003**, *44*, 507–509; b) L. C. Hirayama, K. K. Dunham, B. Singaram, *Tetrahedron Lett.* **2006**, *47*, 5173–5176; c) J. Justicia, I. Sancho-Sanz, E. Álvarez-Manzaneda, J. E. Oltra, J. M. Cuervaa, *Adv. Synth. Catal.* **2009**, *351*, 2295–2300.

[8] a) M. Bandini, P. G. Cozzi, A. Umani-Ronchi, *Polyhedron* **2000**, *19*, 537–539; b) M. Bandini, P. G. Cozzi, P. Melchiorre, R. Tino, A. Umani-Ronchi, *Tetrahedron: Asymmetry* **2001**, *12*, 1063–1069.

[9] M. Inoue, M. Nakada, *Org. Lett.* **2004**, *6*, 2977–2980.

[10] S. Liu, J. T. Kim, C.-G. Dong, Y. Kishi, *Org. Lett.* **2009**, *11*, 4520–4523.

[11] For reviews on TBOx-based catalysis, see: a) H. Yamamoto, G. Xia, *Chem. Lett.* **2007**, *36*, 1082–1087; b) J. P. Abell, H. Yamamoto, *Chem. Soc. Rev.* **2010**, *39*, 61–69.

[12] N. Takenaka, G. Xia, H. Yamamoto, *J. Am. Chem. Soc.* **2004**, *126*, 13198–13199.

[13] G. Xia, H. Yamamoto, *J. Am. Chem. Soc.* **2006**, *128*, 2554–2555.

[14] G. Xia, H. Yamamoto, *J. Am. Chem. Soc.* **2007**, *129*, 496–497.

[15] M. Naodovic, G. Xia, H. Yamamoto, *Org. Lett.* **2008**, *10*, 4053–4055.

[16] a) G. Cahiez, P.-Y. Chavant, *Tetrahedron Lett.* **1989**, *30*, 7373–7376; b) T. Hiyama, M. Sawahata, M. Obayashi, *Chem. Lett.* **1983**, 1237–1238; c) K. Takai, T. Ueda, T. Hayashi, T. Moriwake, *Tetrahedron Lett.* **1996**, *37*, 7049–7052.

[17] It should be noted, that oligomerization of 2-methyltetrahydrofuran was observed during the reaction; the extent of the phenomenon appeared to be substrate-dependent. Calcium carbonate was used as an additive to suppress oligomerization potentially caused by traces of acidic species; this approach resulted only in partial success, indicating the co-existence of an alternative polymerization pathway. Thus, the use of 2-methyltetrahydrofuran as a solvent was applicable only to some of the tested substrates.

[18] K. Takai, K. Nitta, O. Fujimura, K. Utimoto, *J. Org. Chem.* **1989**, *54*, 4732–4734.

[19] a) M. Aresta, M. Rossi, A. Sacco, *Inorg. Chim. Acta* **1969**, *3*, 227–231; b) Y. Yamada, D.-i. Momose, *Chem. Lett.* **1981**, 1277–1278; c) S. K. Bagal, R. M. Adlington, J. E. Baldwin, R. Marquez, *J. Org. Chem.* **2004**, *69*, 9100–9108; d) M. Movassaghi, M. A. Schmidt, *Angew. Chem.* **2007**, *119*, 3799–3802; *Angew. Chem. Int. Ed.* **2007**, *46*, 3725–3728.

[20] a) M. Kurosu, M.-H. Lin, Y. Kishi, *J. Am. Chem. Soc.* **2004**, *126*, 12248–12249; b) K. Namba, Y. Kishi, *Org. Lett.* **2004**, *6*, 5031–5033; c) K. Namba, J. Wang, S. Cui, Y. Kishi, *Org Lett.* **2005**, *7*, 5421–5424; d) Z. Zhang, J. Huang, B. Ma, Y. Kishi, *Org. Lett.* **2008**, *10*, 3073–3076; e) D.-S. Kim, C.-G. Dong, J. T. Kim, H. Guo, J. Huang, P. S. Tiseni, Y. Kishi, *J. Am. Chem. Soc.* **2009**, *131*, 15636–15641.

[21] Under the standard conditions in the presence of all the components except the chromium complex, cobalt additives furnished the corresponding homopropargyl alcohol with the following conversions after 40 h: $[(Ph_3P)_3Co^{I}Cl]$ 47 %, $[(Ph_3P)_2Co^{II}Cl_2]$ 68 %, complex **3** > 95 %, complex **4** 68 %, complex **5** 79 %.

[22] The idea to test complex **5** in order to gain additional information about the phenomenon of cobalt co-catalysis was kindly suggested by a reviewer of this manuscript.