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Synthesis of atropoisomeric pyridines via cobalt-catalyzed cocyclotrimerization of diynes with benzonitrile

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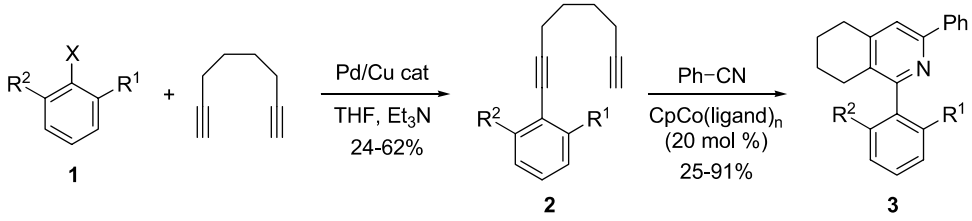
Abstract—Arylpyridines (precursors for potential organocatalysts) are easily accesible by cobalt-catalyzed cocyclotrimerization of *ortho*-substituted 1-aryl-1,7-octadiynes with benzonitrile. The scope of the reaction with respect to the *ortho* substituents (OMe, Me, COOMe, NHCOMe, F, etc.) was investigated. Three potentially atropoisomeric arylpyridines were prepared and one of them was converted into the corresponding *N*-oxide and resolved into its enantiomers. The absolute configuration of the *N*-oxide was established by X-ray crystal structure analysis. Preliminary results of its application in asymmetric organocatalysis are presented.

1. Introduction

The interest in the field of organocatalysis (acceleration of a reaction by a catalytic amount of an organic compound) has increased in the last few years. In particular, organocatalysis is gaining importance in asymmetric synthesis, complementing bio- and metal-catalysis.[1] Out of several concepts of organocatalysis, a significant role is played by activation of a Lewis acid by a Lewis base. One type of the typical Lewis base organocatalysts are pyridine *N*-oxides with a biaryl framework.[2–5] Since pyridine *N*-oxides are easily accessible from pyridines, there is general interest in the development of new synthetic methods for pyridine preparation. One of them is based on [2+2+2] cocyclotrimerization of two C–C-triple bonds with a nitrile.[6] The use of the most widely and generally utilized cobalt catalysts was pioneered by Wakatsuki,[7] Vollhardt,[8] and Bönnemann.[9] Over the years a number of other transition metal compounds such as Ti,[10] Zr,[11] Fe,[12] Ta,[13] and Rh[14] were shown to catalyze or mediate the cyclotrimerization. Recently, a Ru-based catalyst has been shown to be suitable for cyclotrimerization of diynes with electron-deficient nitriles.[15,16] Cocyclotrimerization has also been used for preparation of oligopyridines (namely bipyridines) either by cocyclotrimerization of diynes with dinitriles,[17] or alkynylnitriles with diynes,[18] or cyanopyridines with alkynes.[19] The synthesis of chiral pyridines is based either on cyclotrimerization with chiral nitriles[20] or enantioselective cyclotrimerization by treatment with chiral cyclopentadienyl cobalt complexes.[21] Herein, we report on the cobalt-catalyzed cyclotrimerization of substituted aryldiynes with nitriles to potentially atropoisomeric pyridines, conversion



Scheme 1. Preparation of diynes **2** and their cocyclotrimerization with nitriles to arylpyridines **3** under Co-catalysis.

Keywords: Pyridine; Cocyclotrimerization; Cobalt; Catalysis; Organocatalysis.
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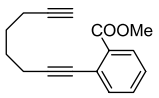
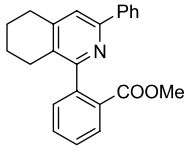
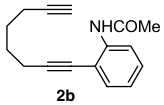
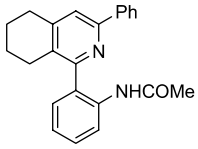
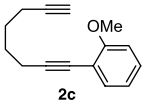
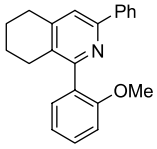
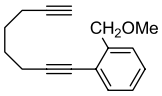
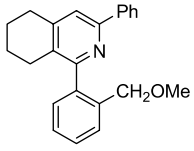
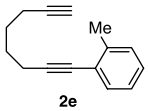
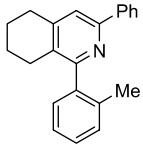
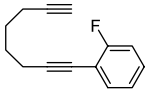
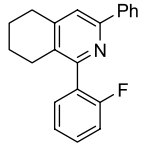
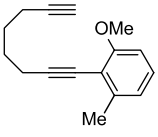
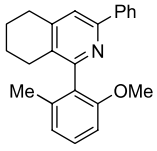
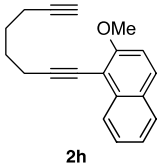
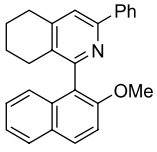
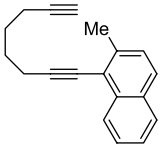
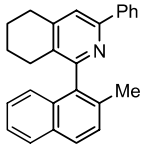
Table 1. Cobalt-catalyzed cocyclotrimerization of diynes **2** with benzonitrile to arylpyridines **3**

Entry	Diyne **2a**	Product **3**	Conditions[a]	Yield %[b]
1	 **2a**	 **3a**	A	54
2	 **2b**	 **3b**	A	35
3	 **2c**	 **3c**	A	76
4	 **2d**	 **3d**	A	33
5	 **2e**	 **3e**	A	91
6	 **2f**	 **3f**	A	46
7	 **2g**	 **3g**	A, B, C	30, 25, 62
8	 **2h**	 **3h**	A, B, C	75 (54)[c], 67, 0
9	 **2i**	 **3i**	A, B, C	30, 69, 48

[a] Conditions: A=$CpCo(CO)_2$ (20 mol%), PPh_3 (40 mol%), 140 °C, 48 h; B=CpCo(COD) (20 mol%), 140 °C, 48 h; C=$CpCo(CH_2{=}CH_2)_2$ (10 mol%), 20 °C, 30 min.
[b] Isolated yields.
[c] $CpCo(CO)_2$ (10 mol%), 140 °C, 48 h.

of one of them into a pyridine *N*-oxide, its resolution into enantiomers, and preliminary results of its application in enantioselective additions to benzaldehyde.

2. Results and discussion

We envisioned that one of the possible pathways to potentially atropoisomeric arylpyridines could be based on the reaction of nitriles with properly substituted α,ω-diynes,[22,23] such as 1-(*ortho*-substituted-aryl)-1,7-octadiynes (Scheme 1). This strategy is similar to that used by Heller et al.[21] but its scope is limited only to a methoxy group as the substituent in the *ortho*-position. It is reasonable to assume that *ortho*-substitution may affect the course of cyclotrimerization by steric and electronic effects. These effects are important in the search for new synthetic methods for preparation of potentially atropoisomeric biaryls. Recently, they have been studied in the Dötz reaction of *ortho*-substituted arylalkynes with chromium carbenes[24] and in the CuCl mediated reaction of zirconacyclopentadienes with *ortho*-substituted arylpropynoates.[25] Furthermore, the synthetic usefulness of the commercially available $CpCo(CO)_2$ was explored.

The required *ortho*-substituted 1-aryl-1,7-octadiynes were prepared by palladium-catalyzed Krause modification[26] of the Sonogashira coupling[27] of 1,7-octadiyne with arylhalides **1** (Scheme 1). Usually, the coupling proceeded smoothly to afford the desired diynes **2** in moderate to reasonable isolated yields (24–62%) and selectivity. To accomplish the cyclotrimerization of the diynes with nitriles, the standard conditions (20 mol% of commercially available $CpCo(CO)_2$, 40 mol% of PPh_3 as a ligand, 140 °C, 2 days) were used (Scheme 1). It has been shown that the catalytically active species are formed in a reasonable reaction rate at this temperature.[6a] Other cobalt complexes such as CpCo(COD) and $CpCo(CH_2{=}CH_2)_2$ (Jonas catalyst)[28,29] were used in order to compare the catalytic activity. The cocyclotrimerizations were carried out in benzonitrile as solvent to minimize homocyclotrimerization of diyne, to ensure a high selectivity ratio for pyridine formation.

The results of cocyclotrimerizations are presented in Table 1. The reaction with the diyne bearing an ester group **2a** afforded the corresponding product **3a** in acceptable yield of 54% (entry 1). In the case of the diyne with a nitrogen substituent such as **2b**, the reaction proceeded only in moderate yield of 35% (entry 2). The cocyclotrimerizations with alkynes bearing methoxy **2c** and methoxymethyl substituents **2d** differed considerably (entries 3 and 4); the product **3c** was obtained in good yield of 76%, whereas the arylpyridine **3d** was isolated in significantly lower yield of 33%. In the case of 1-(*ortho*-tolyl)-1,7-octadiyne **2e** the arylpyridine **3e** was furnished in high yield of 91% (entry 5). The cocyclotrimerization of the fluorine substituted diyne **2f** with benzonitrile also proceeded to give the corresponding arylpyridine **3f** in moderate 46% yield (entry 6).

Cocyclotrimerizations of diynes that were expected to give sterically hindered arylpyridines with restricted rotation about the bond connecting two aromatic rings were far more intriguing (entries 7–9). The reaction of the methoxymethyl substituted diyne **2g** afforded the desired product **3g** in 30% yield (entry 7, conditions A). The use of CpCo(COD) under the same reaction conditions afforded the product in a similar yield of 25% (conditions B). A considerably different result was obtained when the Jonas catalyst (condition C) was used. The full conversion of the starting material was observed within 30 min and **3g** was isolated in good 62% yield. The structure of **3g** was unequivocally confirmed by crystalographic analysis (Fig. 1).

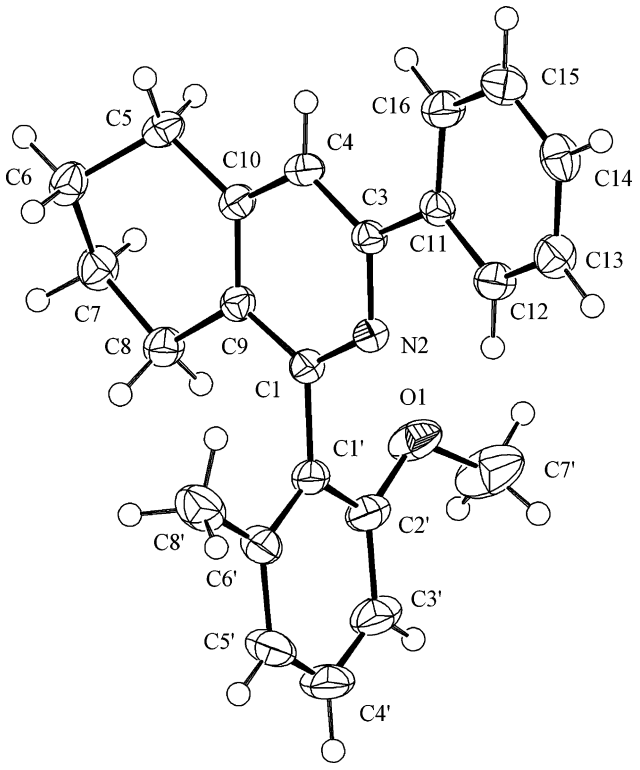
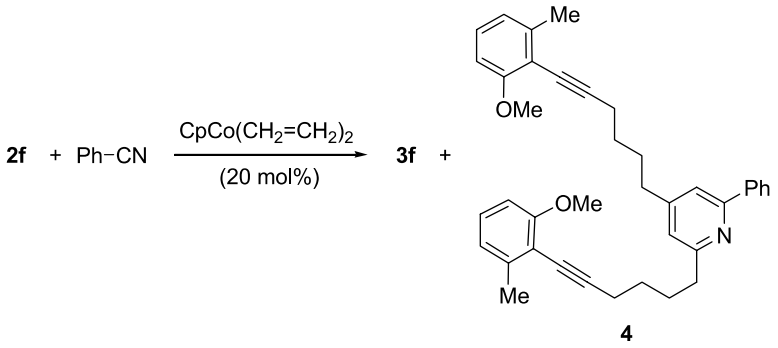


Figure 1. An ORTEP diagram of **3g**. Displacement parameters are shown at the 50% probability level.

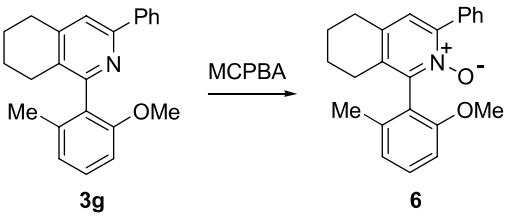
The cyclotrimerization of diyne **2g** was also carried out on 10 mmol scale and the product **3g** was isolated in 45% yield. In addition, it was possible to isolate the compound **4** in 6% yield, which was the product of the cocyclotrimerization of two molecules of **2g** with benzonitrile (Scheme 2). As expected, the reaction with the methoxynaphthyldiyne **2h** furnished the corresponding product **3h** in very good yield of 75% (entry 8, conditions A), which is close to the yield obtained by Heller under different reaction conditions.[21] The similar result was observed under conditions B (67% yield). Surprisingly, the reaction carried out in the presence of the Jonas catalyst did not proceed and the starting material was quantitatively recovered (entry 8, conditions C). The reaction with methylnaphthyldiyne **2i** gave the corresponding product **3i** in rather low yield of 30% (entry 9, conditions A). Again the use the Jonas catalyst (conditions C) resulted in increase of the reaction rate and the conversion of the starting material; the product **3i** was isolated in 48% yield. However, in this instance CpCo(COD) proved to be the catalyst of choice, because



Scheme 2. Formation of **4** in cocyclotrimerization of **2g** and benzonitrile.

its use afforded the corresponding product in 69% yield (conditions B).

The question is what factors are mainly responsible for the observed difference in the yields of the arylpyridines in entries 1–6. Obviously, the differences cannot be simply explained by steric factors, since it is known that for example methyl group occupies larger space than methoxy or ester groups.[30] Although we do not have any spectroscopic evidence for the following hypothesis, it is sensible to assume that the course of the reaction is influenced (retarded) by the strengh of the coordination of the lone electron pair on the heteroatom of the *ortho*-substituent to the cobalt atom in the intermediate cobaltacyclopentadiene.



Scheme 3. Oxidation of the pyridine **3g** to **6**.

Since our initial impetus for this work was to develop an alternative method for the preparation of chiral pyridine oxides as potential organocatalysts, we chose pyridine **3g** for further investigation in this direction. Its oxidation with *m*-chloroperoxobenzoic acid (MPCBA) proceeded smoothly to give the corresponding *N*-oxide **6** in 54% isolated yield (Scheme 3). The *N*-oxide **6** was resolved by cocrystallization with (*S*)-(−)-binol **7** (binol=2,2′-dihydroxy-1,1′-binaphthyl),[2–5] which gave the crystalline

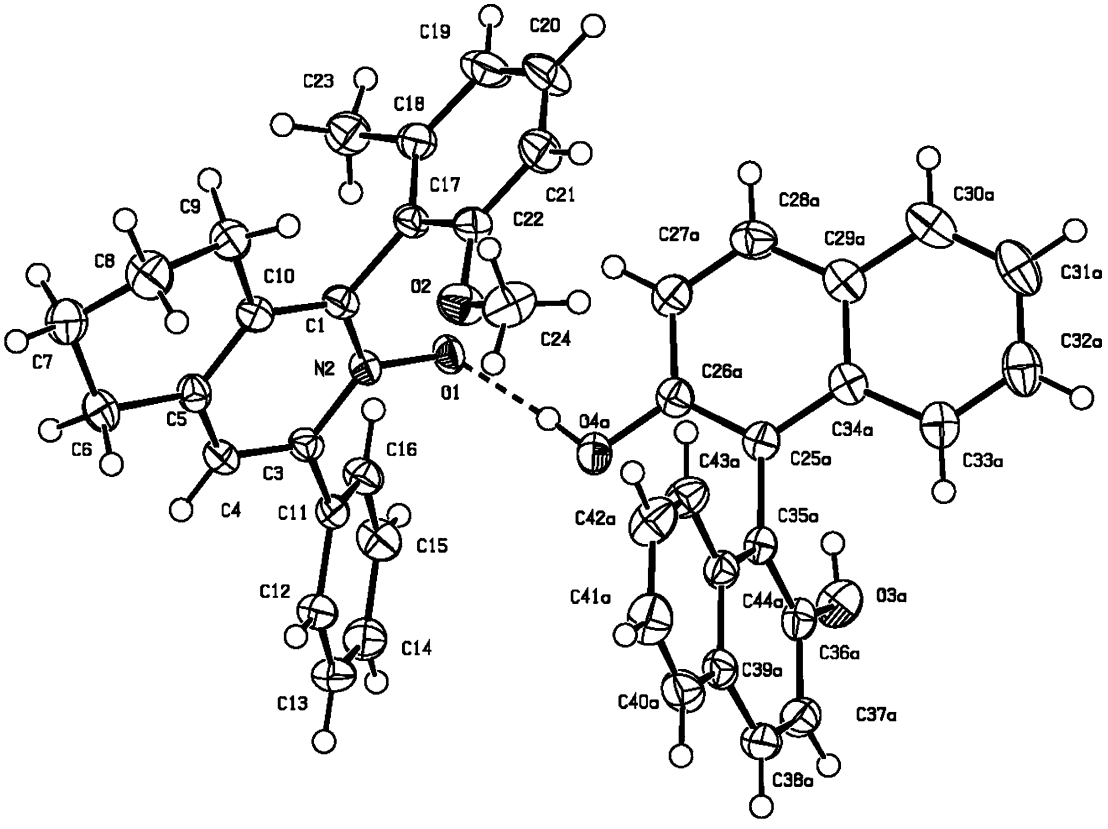
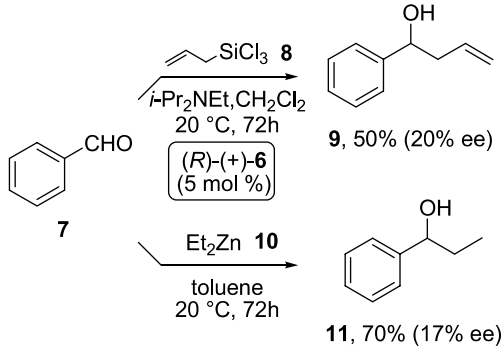


Figure 2. An ORTEP diagram illustrating the interaction of (*R*)-(+)-**6** (on the left) with (*S*)-(−)-**7** (right), in particular the hydrogen bonding N–O···H–O; O(1)···O(4a) 2.606(2) Å, O(1)···H–O(4a) 176(2)°. Displacement parameters are shown at the 50% probability level.

material containing (*S*)-(−)-binol **7** and (+)-**6** (in 1:1 ratio), while (−)-**6** remained in the solution. This cocrystallization, followed by a chromatographic separation of (+)-**6** from (*S*)-(−)-binol **7**, furnished pure (+)-**6** of 95% ee (as detected by chiral HPLC, Chiracel OD-H) in 30% yield. The absolute configuration was found to be (*R*)-(+)-**6** by crystallographic analysis of the molecular crystal of (+)-**6** with (*S*)-(−)-**7** (Fig. 2) of known absolute configuration. The configurational stability of the compound (*R*)-(+)-**6** was quantitatively evaluated by an analytical chiral HPLC. Preliminary data were obtained by heating samples of (*R*)-(+)-**6** and injecting them on the chiral column. The (*R*)-(+)-**6** showed no racemization in toluene at 110 °C after 12 h.

The catalytic activity of the pyridine *N*-oxide (*R*)-(+)-**6** (5 mol%) was preliminarly tested in the addition of allytrichlorosilane **8** to benzaldehyde **7** in dichloromethane (Scheme 4). The attempt to carry out the reaction under usual conditions (−40 °C)[5] was not successful. The reaction proceeded at room temperature only, but even then the reaction rate was rather low, 50% yield of the corresponding alcohol **9** was obtained after 72 h with the modest asymmetric induction of 20% ee. The enantioselectivity of (*R*)-(+)-**6** was also tested in the reaction of diethylzinc **10** with benzaldehyde **7**.[31] The resulting asymmetric induction was again modest (17% ee).



Scheme 4. Enantioselective additions to benzaldehyde **7**.

3. Conclusion

This work has shown that cobalt-catalyzed [2+2+2] cocyclotrimerization of diynes with benzonitrile is a convenient and straightforward method for preparation of not only mono-*ortho*-substituted arylpyridines but also potentially atropoisomeric bis-*ortho*-substituted arylpyridines (entries 7–9, Table 1) in reasonable yields. The starting diynes are easily prepared from the corresponding substituted arylhalides and 1,7-octadiyne in good yields and the use of the commercially available $CpCo(CO)_2$ catalysts gave good yields of the cyclotrimerization products in most cases. Other types of $CpCo(ligand)_n$ (ligand=ethylene, COD) catalysts were tested in cyclotrimerization with bis-*ortho*-substituted aryldiynes but their activity was highly dependent on the structure of the substrate. Last but not least, the racemic arylpyridine-*N*-oxide **6** was resolved into enantiomers and its absolute configuration was unequivocally determined by X-ray structure analysis. Despite the fact that the result of enantioselective additions were not too high, it is premature to rule out the synthetic utility of the pyridine *N*-oxide (*R*)-(+)-**6** at this moment. Further experiments investigating its reactivity and structural modifications will follow in the near future.

4. Experimental

All reactions were carried out under a protective atmosphere of Ar in 20 mL Schlenk flasks. Unless mentioned, reagents were used as obtained without further purification.

4.1. General procedure for catalytic cyclotrimerization of aryl-substituted 1,7-octadiynes with benzonitrile

1-Aryl-1,7-octadiyne (0.4 mmol) and PPh_3 (42 mg, 0.16 mmol) were added to a dry Schlenk tube under argon and dissolved in benzonitrile (2 mL, 19.4 mmol). Then $CpCo(CO)_2$ (14 mg, 0.08 mmol) was added. The reaction mixture was heated for 48 h at 140 °C. After cooling down it was quenched with water and volatiles were removed under reduced pressure. Column chromatography on silica gel was used to isolate products.

4.1.1. Methyl 2-(5,6,7,8-tetrahydro-3-phenylisoquinolin-1-yl)benzoate (3a). Column chromatography on silica gel (7:1 hexane/EtOAc) afforded 192 mg (54%) of the title compound as a viscous liquid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.74–1.84 (m, 4H), 2.44–2.47 (m, 2H), 2.87–2.90 (m, 2H), 3.61 (s, 3H), 7.30–7.47 (m, 6H), 7.54–7.59 (m, 1H), 7.93–7.95 (m, 2H), 7.99–8.01 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 22.4, 23.0, 26.7, 29.5, 52.0, 119.8, 126.9 (2C), 127.7, 128.1, 128.4 (2C), 129.4, 130.0, 130.1, 130.3, 131.6, 139.7, 142.3, 146.6, 153.1, 159.0, 167.7; IR ($CHCl_3$) ν 3523, 3367, 3064, 3005, 2952, 1721, 1590, 1576, 1434, 1295, 1275, 1130, 1084, 1052, 966, 908 cm^{-1}; FAB-MS *m/z* 241 ($M+H^+$), 225, 165, 128, 115; HR-MS (FAB) calculated for $C_{16}H_{17}O_2$ ($M+H^+$) 241.1239, found 241.1229.

4.1.2. *N*-(2-(5,6,7,8-Tetrahydro-3-phenylisoquinolin-1-yl)phenyl)acetamide (3b). Column chromatography on silica gel (1:1 hexane/EtOAc) afforded 96 mg (35%) of the title compound as a pale yellow solid: mp 130–132 °C (hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.72–1.76 (m, 2H), 1.83–1.89 (m, 2H), 1.92 (s, 3H), 2.66–2.69 (m, 2H), 2.92–2.95 (m, 2H), 7.13–7.17 (m, 1H), 7.35–7.51 (m, 6H), 8.01–8.03 (m, 2H), 8.33 (d, J=8.4 Hz, 1H), 9.61 (br s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 22.1, 22.9, 24.8, 27.6, 29.7, 119.7, 122.4, 123.0, 126.2 (2C), 128.4, 128.7 (2C), 128.8, 128.9, 129.9, 131.5, 135.8, 138.5, 149.5, 152.5, 156.0, 168.1; IR ($CHCl_3$) ν 3325, 3065, 3011, 2943, 2864, 1682, 1590, 1521, 1448, 1303, 1242 cm^{-1}; EI-MS *m/z* (% relative intensity) 342 (M^+, 100), 327 (95), 299 (28), 284 (20), 271 (9), 225 (16), 171 (8), 149 (32), 105 (86), 77 (52), 57 (26), 55 (19), 43 (27); HR-MS calculated for $C_{23}H_{22}N_2O$ 342.1732, found 342.1749.

4.1.3. 5,6,7,8-Tetrahydro-1-(2-methoxyphenyl)-3-phenylisoquinoline (3c). Column chromatography on silica gel (4:1 hexane/EtOAc) afforded 97 mg (76%) of the title compound as a viscous liquid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.65–1.85 (m, 4H), 2.33–2.40 (m, 1H), 2.60–2.66 (m, 1H),

2.85–2.90 (m, 2H), 3.77 (s, 3H), 6.95–6.97 (m, 1H), 7.04–7.07 (m, 1H), 7.30–7.42 (m, 6H), 7.96–7.98 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 22.4, 22.9, 25.7, 29.6, 55.5, 110.8, 120.0, 120.7, 127.0 (2C), 128.1, 128.4 (2C), 129.2, 130.4, 130.7, 131.0, 139.9, 146.5, 153.6, 156.6, 157.0; IR ($CHCl_3$) ν 3530, 3063, 2940, 2863, 2837, 1697, 1589, 1555, 1495, 1463, 1278, 1244, 1180, 1109, 1027, 955 cm^{-1}; EI-MS *m/z* (% relative intensity) 315 (M^+, 100), 298 (10), 284 (30), 210 (13); HR-MS calculated for $C_{22}H_{21}NO$ 315.1623, found 315.1638.

4.1.4. 5,6,7,8-Tetrahydro-1-(2-(methoxymethyl)phenyl)-3-phenylisoquinoline (3d). Column chromatography on silica gel (5:2 hexane/EtOAc) afforded 56 mg (33%) of the title compound as a viscous liquid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.71–1.88 (m, 4H), 2.35–2.58 (m, 2H), 2.87–2.91 (m, 2H), 3.25 (s, 3H), 4.33 (s, 3H), 7.16–7.43 (m, 7H), 7.56–7.57 (m, 1H), 7.95–7.97 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 22.3, 23.0, 26.7, 29.6, 58.3, 72.2, 119.9, 125.3, 126.8, 127.2, 127.9, 128.1, 128.2, 128.3, 128.5 (2C), 128.8, 129.0, 130.2, 136.3, 139.4, 153.1, 158.3; IR ($CHCl_3$) ν 3063, 3008, 2935, 2862, 1589, 1432, 1090, 956 cm^{-1}; EI-MS *m/z* (% relative intensity) 329 (M^+, 16), 314 (100), 277 (9), 149 (11), 69 (25), 55 (20), 43 (23); HR-MS calculated for $C_{23}H_{23}NO$ 329.1780, found 329.1768.

4.1.5. 5,6,7,8-Tetrahydro-3-phenyl-1-*o*-tolylisoquinoline (3e). Column chromatography on silica gel (4:1 hexane/EtOAc) afforded 110 mg (91%) of the title compound as a viscous liquid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.71–1.83 (m, 4H), 2.14 (s, 3H), 2.30–2.45 (m, 2H), 2.86–2.89 (m, 2H), 7.19–7.29 (m, 4H), 7.33–7.42 (m, 4H), 7.95–7.98 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 19.6, 22.3, 23.0, 26.5, 29.6, 119.7, 125.5, 126.8 (2C), 127.6, 128.2, 128.5 (2C), 128.6, 129.7, 130.2, 135.7, 139.8, 140.5, 147.1, 153.5, 159.5; IR ($CHCl_3$) ν 3523, 3063, 2942, 2863, 1692, 1589, 1580, 1554, 1432, 1387, 1247, 1178, 1072, 1026 cm^{-1}; EI-MS *m/z* (% relative intensity) 299 (M^+, 100), 284 (65), 270 (20), 257 (26), 165 (9), 128 (8), 103 (8), 84 (27), 49 (7); HR-MS calculated for $C_{22}H_{21}N$ 299.1674, found 299.1672.

4.1.6. 5,6,7,8-Tetrahydro-1-(2-fluorophenyl)-3-phenylisoquinoline (3f). Column chromatography on silica gel (4:1 hexane/EtOAc) afforded 122 mg (46%) of the title compound as a viscous liquid: ^{1}H NMR (400 MHz, C_6D_6) δ 1.41–1.46 (m, 4H), 2.41–2.50 (m, 4H), 2.60–2.66 (m, 1H), 6.63–6.67 (m, 1H), 6.79–6.83 (m, 1H), 6.90–6.96 (m, 2H), 7.16–7.20 (m, 1H), 7.24–7.29 (m, 2H), 7.40–7.45 (m, 1H), 8.16–8.19 (m, 2H); ^{13}C NMR (100 MHz, C_6D_6) δ 23.3, 23.8, 27.0, 30.3, 116.9, 121.5, 125.7 (d, J=3 Hz), 128.6 (2C), 130.2 (2C), 131.2, 132.4, 133.4 (d, J=18 Hz), 141.4, 148.5, 155.5, 156.2, 161.7 (d, J=246 Hz); IR ($CHCl_3$) ν 2941, 1713, 1617, 1590, 1580, 1553, 1494, 1452, 1432, 1423, 1386, 1226, 1099 cm^{-1}; EI-MS *m/z* (% relative intensity) 303 (35), 133 (10), 103 (M^+, 100), 76 (32), 50 (16); HR-MS calculated for $C_{21}H_{18}FN$ 303.1423, found 303.1435.

4.1.7. 5,6,7,8-Tetrahydro-1-(2-methoxy-6-methylphenyl)-3-phenylisoquinoline (3g). Column chromatography on silica gel (4:1 hexane/EtOAc) afforded 121 mg (30%) of the title compound as a white solid: mp 138–139 °C (hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.69–1.83 (m, 4H), 2.03 (s, 3H), 2.04–2.27 (m, 1H), 2.43–2.49 (m, 1H), 2.86–2.89 (m, 2H), 3.71 (s, 3H), 6.81 (d, J=8.4 Hz, 1H), 6.91 (d, J=7.6 Hz, 1H), 7.23–7.27 (m, 1H), 7.31–7.42 (m, 4H), 7.94–7.97 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 19.7, 22.3, 22.8, 25.4, 29.6, 55.6, 108.4, 120.1, 122.7 (2C), 127.1, 128.2, 128.3, 128.4 (2C), 128.6, 131.1, 137.6, 139.8, 146.9, 153.7, 156.4, 156.7; IR ($CHCl_3$) ν 3065, 3025, 3016, 2941, 2863, 2839, 2357, 1591, 1581, 1556, 1470, 1434, 1422, 1387, 1297, 1261, 1230, 1221, 1212, 1087 cm^{-1}; EI-MS *m/z* (% relative intensity) 329 (M^+, 29), 314 (20), 298 (12), 284 (10), 256 (15), 242 (6), 148 (31), 135 (9), 123 (10), 111 (13), 97 (24), 81 (42), 69 (100), 57 (67), 43 (77); HR-MS calculated for $C_{23}H_{23}NO$ 329.1780, found 329.1784. EA calculated for $C_{23}H_{23}NO$ C, 83.85; H, 7.04; N, 4.25. Found C, 83.59; H, 7.08; N, 3.99.

4.1.8. 5,6,7,8-Tetrahydro-1-(2-methoxynaphthalen-1-yl)-3-phenylisoquinoline (3h). Spectral characteritics were in agreement with the previously published data.[21]

4.1.9. 5,6,7,8-Tetrahydro-1-(2-methylnaphthalen-1-yl)-3-phenylisoquinoline (3i). Column chromatography on silica gel (10:1 hexane/EtOAc) afforded 125 mg (30%) of the title compound as a white solid: mp 175–176 °C (hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.63–1.69 (m, 2H), 1.77–1.83 (m, 2H), 2.13–2.22 (m, 2H), 2.22 (s, 3H), 2.91–2.94 (m, 2H), 7.22–7.24 (m, 1H), 7.29–7.50 (m, 7H), 7.79–7.84 (m, 2H), 7.96–7.98 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.0, 22.3, 22.9, 25.6, 29.7, 120.1, 124.7, 125.1, 126.0, 126.9 (2C), 127.6, 127.9, 128.3, 128.5 (2C), 128.8, 131.0, 131.9, 132.1, 133.1, 136.6, 139.8, 147.2, 154.3, 158.1; IR ($CHCl_3$) ν 3059, 3024, 3015, 2941, 2356, 1591, 1556, 1508, 1494, 1381, 1315, 1260, 1229, 1219, 1205, 1198, 1085, 915, 866, 813 cm^{-1}; EI-MS *m/z* (% relative intensity) 349 (M^+, 100), 334 (65), 320 (16), 307 (14), 256 (7), 166 (8), 149 (46), 139 (8), 111 (10), 97 (16), 83 (24), 69 (42), 57 (56), 43 (59); HR-MS calculated for $C_{26}H_{23}N$ 349.1830, found 349.1839. EA calculated for $C_{26}H_{23}N$ C, 89.36; H, 6.63; H 4.01. Found C, 88.86; H, 6.67; H, 3.76.

4.1.10. ($\pm$)-5,6,7,8-Tetrahydro-1-(2-methoxy-6-methylphenyl)-3-phenylisoquinoline-*N*-oxide (6). To a solution of pyridine **3f** (160 mg, 0.48 mmol) in dichloromethane (2 mL) was added MCPBA (purity 70%) (220 mg, 0.93 mmol) at 0 °C. After stirring of the resulting mixture at room temperature for 1 h it was quenched by the saturated water solution of $NaHCO_3$ (1 mL) and the crude product was extracted with dichloromethane (5 mL). The organic layer was separated and column chromatography on silica gel (ethyl acetate) afforded 90 mg (54%) of the title compound **6** as a viscous liquid: ^{1}H NMR (400 MHz, C_6D_6) δ 1.32–1.44 (m, 4H), 2.06–2.14 (m, 2H), 2.16 (s, 3H), 2.26–2.33 (m, 2H), 3.25 (s, 3H), 6.56 (d, J=8.2 Hz, 1H), 6.91 (d, J=7.6 Hz, 1H), 7.01–7.06 (m, 1H), 7.10–7.22 (m, 4H), 7.96–7.98 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 19.9, 23.1, 23.3, 27.1, 29.2, 56.2, 109.8, 123.6, 123.9, 126.8, 128.6 (2C), 129.5, 130.3, 130.6 (2C), 134.0, 134.7, 135.4, 139.5, 146.9, 148.0, 158.0; IR ($CHCl_3$) ν 3614, 3010, 2971, 1582, 1467, 1387, 1257, 1127, 1080, 945 cm^{-1}; EIS-MS *m/z* 346 (M^++H), 352 (M^+−O+Na), 368 (M^++Na).

4.1.11. (*R*)-(+)-5,6,7,8-Tetrahydro-1-(2-methoxy-6-methylphenyl)-3-phenylisoquinoline-*N*-oxide ((*R*)-(+)-6). To a solution of (*S*)-(−)-binol **7** (293 mg, 0.99 mmol) and racemic 5,6,7,8-tetrahydro-1-(2-methoxy-6-methylphenyl)-3-phenylisoquinoline-*N*-oxide **6** (340 mg, 0.99 mmol) in dichloromethane (5 mL) heptane (10 mL) was added, the flask was closed with a septum with a needle and set aside to allow slow evaporation of dichloromethane through the needle. The molecular complex (*R*)-(+)-**6**·(*S*)-(−)-**7** crystallized within 5 days as colorless needles that were collected by suction filtration. Individual components were collected by column chromatography on silica gel (ethyl acetate), which afforded 105 mg (30%) of (*R*)-(+)-**6**. Chiral HPLC (Chiralcel OD-H, 0.46×25 cm, 8:1 heptane/2-propanol, 1.2 mL min^{-1}) showed 95% ee depending on the batch (t_S=8.01 min, t_R=9.12 min).

4.2. Enantioselective allylation of benzaldehyde with allyltrichlorosilane to (*R*)-(+)-1-phenyl-but-3-en-1-ol (9)

To a solution of (*R*)-(+)-**6** (5 mg, 0.014 mmol) in dichloromethane (1.4 mL) were added benzaldehyde (40 μL, 0.4 mmol), diisopropylethylamine (87 μL, 0.5 mmol), and allyltrichlorosilane (75 μL, 0.47 mmol) at 0 °C. The reaction mixture was stirred at 20 °C for 72 h. The reaction was quenched with saturated aqueous $NaHCO_3$ (1 mL), the layers were separated and dried over $MgSO_4$. GC yield of **9** was 50%. Chiral GC (HP-Chiral β 30 m×0.25 mm, oven: 80 °C for 15 min, then 1 °C/min to 150°C, 5 min at that temperature) showed 20% ee (t_R=57.55 min, t_S=56.03 min).

4.3. Enantioselective alkylation of benzaldehyde with diethylzinc to (*R*)-(+)-1-phenyl-1-propanol (11)

To a solution of (*R*)-(+)-**6** (7 mg, 0.02 mmol) in toluene (0.6 mL) 1 M solution of diethyl zinc hexane (0.68 mL, 0.68 mmol) was added at 0 °C and the reaction mixture was stirred for 20 min. Then benzaldehyde (33 μL, 0.33 mmol), was added and the reaction mixture was stirred for 72 h at 20 °C. The reaction was quenched with 10% H_2SO_4 (0.5 mL), the organic layer was separated and the aqueous phase was extracted with diethylether, the combined organic layers were dried over $MgSO_4$. GC yield of the 1-phenyl-1-propanol was 62%. Chiral GC (HP-Chiral β 30 m×0.25 mm, oven: 80 °C for 15 min, then 1 °C/min to 150 °C, 5 min at that temperature) showed 17% ee (t_R=49.78 min, t_S=51.09 min).

4.4. Crystallography

Crystal data for: **3g**. $C_{23}H_{23}NO$, M=329.42, monoclinic, $P2_1/n$, a=13.1910(3) Å, b=8.6090(2) Å, c=16.4300(4) Å, β=107.1860(11)°, V=1782.50(7) $Å^3$, Z=4, D_x=1.228 Mg m^{-3}. A colorless prism dimensions 0.5×0.25×0.2 mm was mounted on glass capillary with epoxy glue and measured at Nonius KappaCCD diffractometer by monochromatized Mo Kα radiation (λ=0.71073 Å) at 150(2) K. An absorption was neglected (μ=0.074 mm^{-1}); a total of 26146 measured reflections in the range h=−17 to 17, k=−11 to 11, l=−21 to 21 (θ_{max}=27.5°), from which 4076 were unique (R_{int}=0.015), 3294 observed according to the $I>2\sigma(I)$ criterion. The structure was solved by direct methods (SIR92)[32] and refined by full-matrix least squares based on F^2 (SHELXL97).[33] The hydrogen atoms were recalculated into idealised positions (riding model) and assigned displacement parameter either $H_{iso}(H)$=1.2 U_{eq}(pivot atom) or $H_{iso}(H)$=1.5 U_{eq}(pivot atom) for methyl moiety. The refinement converged (Δ/σ_{max}=0.001) to R=0.0447 for observed reflections and wR=0.124, S=1.038 for 229 parameters and all 4076 reflections. The final difference map displayed no peaks of chemical significance ($\Delta\rho_{max}$=0.252, $\Delta\rho_{min}$ −0.246 e$Å^{-3}$).

Crystal data for (*R*)-(+)-**6**·(*S*)-(−)-**7**: $C_{23}H_{23}NO_2 \cdot C_{20}H_{14}O_2$, M=631.74, monoclinic, $P2_1$, a=11.5900(3) Å, b=9.0280(2) Å, c=16.0570(4) Å, β=104.4160(13)°, V=1627.22(7) $Å^3$, Z=2, D_x=1.289 Mg m^{-3}. A colorless plate of dimensions 0.37×0.2×0.15 mm was mounted on glass capillary with epoxy glue and measured at Nonius KappaCCD diffractometer by monochromatized Mo Kα radiation (λ=0.71073 Å) at 150(2) K. An absorption was neglected (μ=0.082 mm^{-1}); a total of 19962 measured reflections in the range h=−15 to 15, k=−11 to 11, l=−20 to 20 (θ_{max}=27.5°), from which 7408 were unique (R_{int}=0.028), 6678 observed according to the $I>2\sigma(I)$ criterion. The structure was solved by direct methods (SIR92)[32] and refined by full-matrix least squares based on F^2 (SHELXL97).[33] The absolute configuration of the crystal has been assigned by reference of known configuration of (*S*)-(−)-binol **7**. The hydrogen atoms were found on difference Fourier map, those on carbon atoms were recalculated into idealised positions (riding model) and assigned displacement parameter either $H_{iso}(H)$=1.2 U_{eq}(pivot atom) or $H_{iso}(H)$=1.5 U_{eq}(pivot atom) for methyl moiety. The hydrogen of the hydroxyl moiety was refined isotropically. The refinement converged (Δ/σ_{max}=0.000) to R=0.0378 for observed reflections and wR=0.0956, S=1.001 for 443 parameters and all 7408 reflections. The final difference map displayed no peaks of chemical significance ($\Delta\rho_{max}$=0.259, $\Delta\rho_{min}$ −0.181 e$Å^{-3}$).

Crystallographic data for structural analysis have been deposited with the Cambridge Crystallographic Data Centre, CCDC no. 283868 and 283869 for **3g** and (*R*)-(+)-**6**·(*S*)-(−)-**7**, respectively. Copies of this information may be obtained free of charge from The Director, CCDC, 12 Union Road, Cambridge CB2 1EY, UK (fax: +44 1223 336033; e-mail: deposit@ccdc.cam.ac.uk or www: http://www.ccdc.cam.ac.uk).

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Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tet.2005.10.034. Preparation and spectral characteristics of the starting 1-aryl-1,7-diynes **2** and the pyridine **4**.

References and notes

1. For a general concept of organocatalysis and typical examples, see: (a) Dalko, P. I.; Moisan, L. *Angew. Chem., Int. Ed.* **2001**, *40*, 3726–3748. (b) Malkov, A.; Kočovský, P. *Curr. Org. Chem.* **2003**, *7*, 1737–1757. (c) Palomo, C.; Oiarbide, M.; Garcia, J. M. *Chem. Soc. Rev.* **2004**, *33*, 65–75. (d) Chelucci, G.; Murineddu, G.; Pinna, G. A. *Tetrahedron: Asymmetry* **2004**, *15*, 1373–1389. (e) Dalko, P. I.; Moisan, L. *Angew. Chem., Int. Ed.* **2004**, *43*, 5135–5175. (f) Seayad, J.; List, B. *Org. Biomol. Chem.* **2005**, *3*, 719–724.
2. (a) Nakajima, M.; Saito, M.; Shiro, M.; Hashimoto, S. *J. Am. Chem. Soc.* **1998**, *120*, 6419–6420. (b) Nakajima, M.; Saito, M.; Hashimoto, S. *Chem. Pharm. Bull.* **2000**, *48*, 306–307. (c) Nakajima, M.; Saito, M.; Hashimoto, S. *Tetrahedron: Asymmetry* **2002**, *13*, 2449–2452. (d) Nakajima, M.; Saito, M.; Uemura, M.; Hashimoto, S. *Tetrahedron Lett.* **2002**, *43*, 8824–8827. (e) Nakajima, M.; Yokota, T.; Saito, M.; Hashimoto, S. *Tetrahedron Lett.* **2004**, *45*, 61–64.
3. (a) Shimada, T.; Kina, A.; Ikeda, S.; Hayashi, T. *Org. Lett.* **2002**, *4*, 2799–2801. (b) Shimada, T.; Kina, A.; Hayashi, T. *J. Org. Chem.* **2003**, *68*, 6329–6337.
4. (a) Malkov, A. V.; Orsini, M.; Pernazza, D.; Muir, K. W.; Langer, V.; Meghani, P.; Kočovský, P. *Org. Lett.* **2002**, *2*, 1047–1049. (b) Malkov, A. V.; Bell, M.; Orsini, M.; Pernazza, D.; Massa, A.; Herrmann, P.; Meghani, P.; Kočovský, P. *J. Org. Chem.* **2003**, *68*, 9659–9668. (c) Malkov, A. V.; Pernazza, D.; Bell, M.; Bella, M.; Massa, A.; Teplý, F.; Meghani, P.; Kočovský, P. *J. Org. Chem.* **2003**, *68*, 4727–4742. (d) Malkov, A. V.; Bell, M.; Vassieu, M.; Bugatti, V.; Kočovský, P. *J. Mol. Catal. A* **2003**, *196*, 179–186.
5. Malkov, A.; Dufková, L.; Farrugia, L.; Kočovský, P. *Angew. Chem., Int. Ed.* **2003**, *42*, 3674–3677.
6. For reviews see: (a) Bönnemann, H.; Brijoux, W. *Adv. Heterocycl. Chem.* **1990**, *48*, 177–222. (b) Shore, N. E. In *[2+2+2] Cycloadditions*; Trost, B. M., Fleming, I., Paquette, L. A., Eds.; Comprehensive Synthesis; Pergamon: Oxford, 1991; Vol. 5, pp 1129–1162. (c) Grotjahn, D. B. In *Transition Metal Alkyne Complexes: Transition Metal-Catalyzed Cyclotrimerization*; Abel, E. W., Stone, F. G. A., Wilkinson, G., Hegedus, L. S., Eds.; Comprehensive Organometallic Chemistry II; Pergamon: Oxford, 1995; Vol. 12, p 741. (d) Bönnemann, H.; Brijoux, W. In *Cyclomerization of Alkynes*; Beller, M., Bolm, C., Eds.; Transition Metals for Organic Synthesis; Wiley: Weinheim, Germany, 1998; Vol. 1, pp 114–135. (e) Varela, J. A.; Saá, C. *Chem. Rev.* **2003**, *103*, 3787–3801.
7. (a) Wakatsuki, Y.; Yamazaki, H. *J. Chem. Soc., Chem. Commun.* **1973**, 280. (b) Wakatsuki, Y.; Yamazaki, H. *Tetrahedron Lett.* **1973**, 3383–3384. (c) Wakatsuki, Y.; Yamazaki, H. *J. Chem. Soc., Dalton Trans.* **1978**, 1278–1282.
8. Vollhardt, K. P. C.; Bergman, R. G. *J. Am. Chem. Soc.* **1974**, *96*, 4996–4998.
9. Bönnemann, H.; Brinkmann, R.; Schenkluhn, H. *Synthesis* **1974**, 575–577.
10. Ti-mediated. (a) Hill, J. E.; Balaich, G.; Fanwick, P. E.; Rothwell, I. P. *Organometallics* **1993**, *12*, 2911–2924. (b) Suzuki, D.; Tanaka, R.; Urabe, H.; Sato, F. *J. Am. Chem. Soc.* **2002**, *124*, 3518–3519.
11. Zr-mediated. (a) Takahashi, T.; Tsai, F.; Kotora, M. *J. Am. Chem. Soc.* **2000**, *122*, 4994–4995. (b) Takahashi, T.; Tsai, F.; Li, Y.; Wang, H.; Kondo, Y.; Yamanaka, M.; Nakajima, K.; Kotora, M. *J. Am. Chem. Soc.* **2002**, *124*, 5059–5067.
12. Fe-mediated. Ferré, K.; Toupet, L.; Guerchais, V. *Organometallics* **2002**, *21*, 2578–2580.
13. Ta-mediated. (a) Smith, D. P.; Strickler, J. R.; Gray, S. D.; Bruck, M. A.; Holmes, R. S.; Wigley, D. E. *Organometallics* **1992**, *11*, 1275–1288. (b) Takai, K.; Yamada, M.; Utimoto, K. *Chem. Lett.* **1995**, 851–852.
14. Rh-catalyzed. (a) Cioni, P.; Diversi, P.; Ingrosso, G.; Lucherini, A.; Ronca, P. *J. Mol. Catal.* **1987**, *40*, 337–357. (b) Cioni, P.; Diversi, P.; Ingrosso, G.; Lucherini, A.; Ronca, P. *J. Mol. Catal.* **1987**, *40*, 359–377. (c) Diversi, P.; Ermini, L.; Ingrosso, G.; Lucherini, A. *J. Organomet. Chem.* **1993**, *447*, 291–298. (d) Costa, M.; Dias, F. S.; Chiusoli, G. P.; Gazzola, G. L. *J. Organomet. Chem.* **1995**, *488*, 47–53. (e) Costa, M.; Dalcanale, E.; Dias, F. S.; Graiff, C.; Tiripicchio, A.; Bigliardi, L. *J. Organomet. Chem.* **2001**, *619*, 179–193. (f) Rh-mediated. Bianchini, C.; Meli, A.; Peruzzini, M.; Vacca, A.; Vizza, F. *Organometallics* **1991**, *10*, 645–651.
15. (a) Yamamoto, Y.; Okuda, S.; Itoh, K. *Chem. Commun.* **2001**, 1102–1103. (b) Yamamoto, Y.; Ogawa, R.; Itoh, K. *J. Am. Chem. Soc.* **2001**, *123*, 6189–6190. (c) Yamamoto, Y.; Takagishi, H.; Itoh, K. *Org. Lett.* **2001**, *3*, 2117–2119. (d) Yamamoto, Y.; Takagishi, H.; Itoh, K. *J. Am. Chem. Soc.* **2002**, *124*, 28–29. (e) Yamamoto, Y.; Kinpara, K.; Saigoku, T.; Takagishi, T.; Okuda, S.; Nishiyama, H.; Itoh, K. *J. Am. Chem. Soc.* **2005**, *127*, 605–613.
16. Varela, J. A.; Castedo, L.; Saá, C. *J. Org. Chem.* **2003**, *68*, 8595–8598.
17. (a) Varela, J. A.; Castedo, L.; Saá, C. *J. Org. Chem.* **1997**, *62*, 4189–4192. (b) Varela, J. A.; Castedo, L.; Saá, C. *J. Am. Chem. Soc.* **1998**, *120*, 12147–12148. (c) Varela, J. A.; Castedo, L.; Maestro, M.; Mahía, J.; Saá, C. *Chem. Eur. J.* **2001**, *7*, 5203–5213.
18. Varela, J. A.; Castedo, L.; Saá, C. *Org. Lett.* **1999**, *1*, 2141–2143.
19. Bönnemann, H.; Brinkmann, R. *Synthesis* **1975**, 600–602.
20. (a) Heller, B.; Sundermann, B.; Fischer, C.; You, J.; Chen, W.; Drexler, H.-J.; Knochel, P.; Bonrath, W.; Gutnov, A. *J. Org. Chem.* **2003**, *68*, 9221–9225. (b) Hoshi, T.; Katano, M.; Nozawa, E.; Suzuki, T.; Hagiwara, H. *Tetrahedron Lett.* **2004**, *45*, 3489–3491.
21. Gutnov, A.; Heller, B.; Fischer, C.; Drexler, H.-J.; Spannenberg, A.; Sundermann, B.; Sundermann, C. *Angew. Chem., Int. Ed.* **2004**, *43*, 3795–3797.
22. For reaction of α,ω-diynes with nitriles, see: (a) Naiman, A.; Vollhardt, K. P. C. *Angew. Chem., Int. Ed. Engl.* **1977**, *16*, 708–709. (b) Brien, D. J.; Naiman, A.; Vollhardt, K. P. C. *J. Chem. Soc., Chem. Commun.* **1982**, 133–134. (c) Chiusoli, G. P.; Pallini, L.; Terenghi, G. *Transition Met. Chem.* **1983**, *8*, 250–252. (d) Battaglia, L. P.; Delledonne, D.; Nardelli, M.; Predieri, G.; Chiusoli, G. P.; Costa, M.; Pelizzi, C. *J. Organomet. Chem.* **1989**, *363*, 209–222. (e) Zhou, Z.; Battaglia, L. P.; Chiusoli, G. P.; Costa, M.; Nardelli, M.; Pelizzi, C.; Predieri, G. *J. Organomet. Chem.* **1991**, *417*, 51–63. (f) Vitulli, G.; Bertozzi, S.; Lazzaroni, R.; Salvadori, P. *J. Organomet. Chem.* **1986**, *307*, C35–C37. (g) Vitulli, G.; Bertozzi, S.; Vignali, M.; Lazzaroni, R.; Salvadori, P. *J. Organomet. Chem.* **1987**, *326*, C33–C36. (h) Moretto, A. F.; Zhang, H.-C.; Maryanoff, B. E. *J. Am. Chem. Soc.* **2001**, *123*, 3157–3158. (i) Yong, L.; Butenschön, H. *Chem. Commun.* **2002**, 2852–2853. (j) Hoshi, T.; Katano, M.; Nozawa, E.; Suzuki, T.; Hagiwara, H. *Tetrahedron Lett.* **2004**, *45*, 3489–3491.

23. For reaction of α,β-diynes with nitriles in natural product synthesis, see: (a) Parnell, C. A.; Vollhardt, K. P. C. *Tetrahedron* **1985**, *41*, 5791–5796. (b) Geiger, R. E.; Lalonde, M.; Stoller, H.; Schleich, K. *Helv. Chim. Acta* **1984**, *67*, 1274–1282. (c) Saá, C.; Crotts, D. D.; Hsu, G.; Vollhardt, K. P. C. *Synlett* **1994**, 487–489.
24. (a) Anderson, J. C.; Cran, J. W.; King, N. P. *Tetrahedron Lett.* **2002**, *43*, 3849–3852. (b) Anderson, J. C.; Cran, J. W.; King, N. P. *Tetrahedron Lett.* **2003**, *44*, 7771–7774.
25. Dufková, L.; Kotora, M.; Císařová, I. *Eur. J. Org. Chem.* **2005**, 2491–2499.
26. Thorand, S.; Krause, N. *J. Org. Chem.* **1998**, *63*, 8851–8853.
27. (a) Sonogashira, K.; Tohda, Y.; Hagihara, N. *Tetrahedron Lett.* **1975**, 4467–4470. (b) Takahashi, S.; Kuroyama, Y.; Sonogashira, K.; Hagihara, N. *Synthesis* **1980**, 627–630.
28. For preparation see: (a) Jonas, K.; Deffense, D.; Habermann, D. *Angew. Chem., Int. Ed. Eng.* **1983**, *22*, 716–718. (b) Cammack, J. K.; Jalisatgi, S.; Matzger, A. J.; Negrón, A.; Vollhardt, K. P. C. *J. Org. Chem.* **1996**, *61*, 4798–4800.
29. Jonas catalyst is very reactive and promotes cocyclotrimerization of alkynes with nitriles already at 20 °C. (a) See Ref. 28a. (b) Diversi, P.; Ingrosso, G.; Lucherini, A.; Vanacore, D. *J. Mol. Catal.* **1987**, *41*, 261–270. (c) Bönnemann, H.; Brijoux, W. *New J. Chem.* **1987**, *11*, 549–559. (d) Schulz, W.; Preacejus, H.; Oehme, G. *Tetrahedron Lett.* **1989**, *30*, 1229–1232. (e) See Ref. 18
30. *Stereochemistry of Organic Compounds*; Eliel, E. L., Wilen, S. H., Eds.; Wiley: New York, 1994; p 1144.
31. For leading reference, see: Derdau, V.; Laschat, S.; Hupe, E.; König, W. A.; Dix, I.; Jones, P. G. *Eur. J. Inorg. Chem.* **1999**, 1001–1007.
32. Altomare, A.; Cascarano, G.; Giacovazzo, C.; Guagliardi, A.; Burla, M. C.; Polidori, G.; Camalli, M. *J. Appl. Cryst.* **1994**, *27*, 435.
33. Sheldrick, G. M. *SHELXL97*: *Program for crystal structure refinement from refraction data*; University of Göttingen: Germany, 1997.