Synthesis and Characterization of New Enantiopure 7,7′-Disubstituted 2,2′-Dihydroxy-1,1′-binaphthyls: Useful Ligands for the Asymmetric Allylation Reaction of Aldehydes

Marco Bandin,[a] Sonia Casolari,[a] Pier Giorgio Cozzi,[a] Gloria Proni,[b] Erick Schmohel,[a] Gian Piero Spada,[b] Emilio Tagliavini,[a] and Achille Umani-Ronchi[a]

Keywords: Binaphthol / 7,7′-Dibromo-Binaphthols / Absolute configuration / Chiroptical properties / Enantioselective catalysis

As an extension of our interest in developing new enantioselective reactions based on the binaphthol *privileged ligand*, we report a simple approach to the synthesis of 7,7′-disubstituted binaphthols. The commercially available 1,7-dihydroxynaphthalene (**1**) was used as starting material for the preparation of the bromoderivatives **2**, which were oxidatively coupled to afford **3**, a key intermediate for the preparation of a variety of enantiopure substituted binaphthols (**8**, **10**). The absolute configuration of the new compounds was established by chiroptical analysis and by cholesteric induction. The optically active catalysts derived from the ligands **3**, **8**, **10**, **16** and **17**, complexed with Ti(O*i*Pr)2Cl2, Zr(O*i*Pr)4 and ZrCl4(THF)2, were employed for the enantioselective addition of allyltributyltin to aldehydes. Finally, the influence of the substituent of the binaphthyl core on the transmission of the chiral information was also investigated.

Introduction

Due to the interest in enantiopure 2,2′-dihydroxy-1,1′-binaphthyl (BINOL) as a chiral information source in catalytic[1] and stoichiometric[2] organic reactions, the synthesis of enantiomerically pure disubstituted BINOLs has started to attract the increasing attention of the chemical community. In this context, disubstitued BINOLs were used to prepare new efficient Lewis acids,[3] heterobimetallic catalysts,[4] polymeric catalysts,[5] chiral polymers[6] and novel optical materials.[7] In particular, 3,3′- and 6,6′-dibromobinaphthyl derivatives appear important for the synthesis of alkyl and aryl 3,3′- and 6,6′- disubstituted BINOLs.[8]

Although a few 7,7′-disubstituted 2,2′-dihydroxy-1,1′-binaphthyls have been synthesized in optically active form,[9] a general and simple approach for the preparation of these compounds is still lacking. In this paper, we report the straightforward synthesis and resolution of the title compounds (Figure 1) which are useful ligands for the preparation of new catalysts and for material science. These disubstituted BINOLs were completely characterized by analytical and chiroptical studies and were utilized to promote the asymmetric allylation reaction of aldehydes.

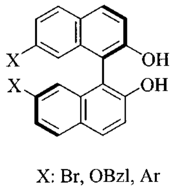
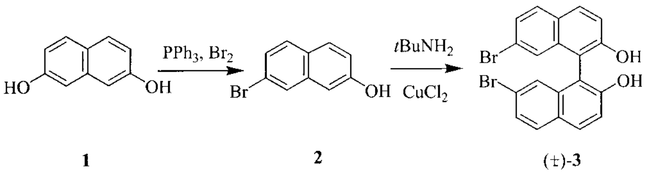


Figure 1. Substituted BINOLs

Results and Discussion

Synthesis of BINOLs

2,7-Dihydroxynaphthalene (**1**) was converted into 7-bromo-2-hydroxynaphthalene (**2**)[10] in moderate yield by the well-established procedure which was reported for alkyl and aryl alcohols.[11] Finally, the preparation of the desired binaphthol **3** was achieved by oxidative coupling of **2**[12] (Scheme 1).



Scheme 1. Synthesis of (±)-7,7′-dibromo-2,2′-dihydroxy-1,1′-binaphthyl (**3**)

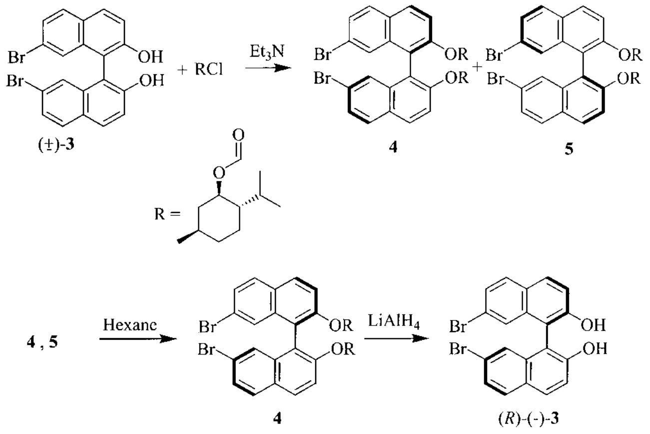
The resolution of (±)-7,7′-dibromo-2,2′-dihydroxy-1,1′-binaphthyl (**3**) was carried out according to the general procedure introduced by De Lucchi.[13] Thus, **3** was treated with the (1*R*,2*S*,5*R*)-(−)-menthyl chloroformate in the presence of triethylamine, and the resulting diastereoisomeric

---

[a] Dipartimento di Chimica “G. Ciamician”,
Università di Bologna,
Via Selmi 2, I-40126 Bologna, Italy
E-mail: umani@ciam.unibo.it
[b] Dipartimento di Chimica Organica “A. Mangini”,
Università di Bologna,
Via S. Donato 15, I-40127 Bologna, Italy
E-mail: gpspada@alma.unibo.it

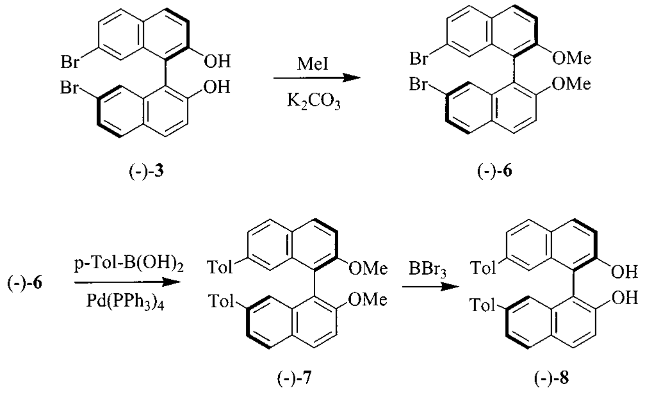
1434−193X/00/0203−0491 $ 17.50+.50/0

mixture of the bis(menthyl) carbonates **4** and **5** was isolated in good yield. The subsequent recrystallization from hexane afforded the pure diasteroisomer **4**, which was reduced to the enantiopure (−)-**3** by an excess of $LiAlH_4$ (Scheme 2).



Scheme 2. Resolution of (±)-**3**

The efficiency of our method was confirmed by the high optical purity of **3**, which was isolated with an enantiomeric excess (ee) of 99.9% (see Experimental Section). Compound **3** is a useful starting material for the preparation of new 7,7′-disubstituted 2,2′-dihydroxy-1,1′-binaphthyl derivatives. As a representative example, we decided to synthesize a 7,7′-diaryl-substituted binaphthol. Thus, the *O*-protected BINOL **6** was coupled to 4-methylphenylboronic acid, following the well-known Suzuki[14] procedure, affording (−)-7,7′-bis(4-methylphenyl)-2,2′-dimethoxy-1,1′-binaphthyl (**7**) in 81% yield. Finally, treatment of (−)-**7** with BBr_3 gave the desired (−)-7,7′-bis(4-methylphenyl)-2,2′-dihydroxy-1,1′-binaphthyl (**8**) in 78% yield (Scheme 3).



Scheme 3. Synthesis of (−)-7,7′-bis(4-methylphenyl)2,2′-dihydroxy-1,1′-binaphthyl (**8**)

Determination of the Absolute Configuration of BINOLs

Because of the nonplanar arrangement of the two naphthalene rings in the 1,1′-binaphthyl compounds, this class of molecules is axially chiral. In these compounds, the *s-cis* and the *s-trans* conformations are characterized by opposite helicities along the biaryl axis (Figure 2). For this reason, the analysis of the circular dichroism (CD) spectra proved to be useful in solving stereochemical problems.[15][16] Later on, the technique of the induction of cholesteric phases in nematic liquid crystals was largely employed as well.[17] We therefore assigned the absolute configurations of the new compound by both these approaches.

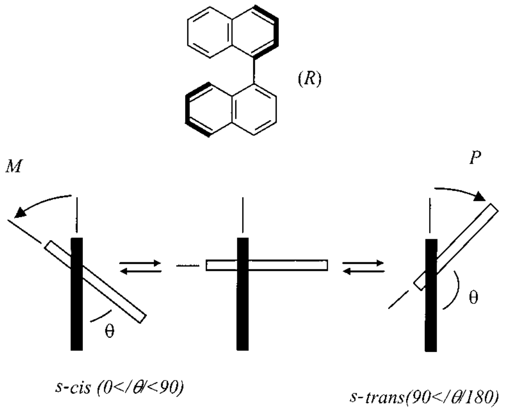


Figure 2. Helicity of the *s-cis* and *s-trans* conformation of (*R*)-1,1′-binaphthalene

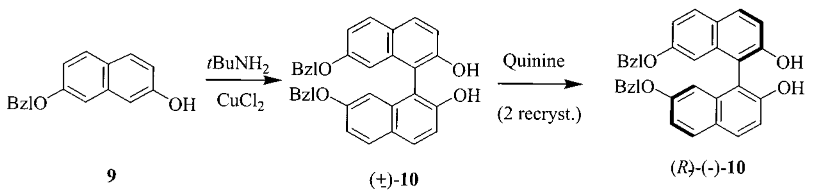
CD spectroscopy exploits the analysis of the exciton couplet originating from the ^1B electronic transition of the naphthalene chromophore at about 230 nm. When the absolute configuration is (*R*), an *s-cis* conformation gives rise to a couplet with a negative branch at low energy and a positive one at high energy (negative couplet). However, when the dihedral angle θ between the naphthyl moieties increases and reaches a critical value, the couplet vanishes (and then subsequently inverts its sign): this critical angle was estimated to be around 100−110° for the unsubstituted 1,1′-binaphthalene.[15]

In this work we examined the chiroptical properties of this new class of BINOLs (**10**, **11**, **12**). The disubstituted BINOL (*R*)-(−)-**10** was prepared according to the method published by Diederich[9a] (Scheme 4), and was converted to the the cyclic (*R*)-(−)-**11** upon treatment with dibromomethane, while (*R*)-(−)-**12** was obtained from an analogous reaction starting from (*R*)-(−)-**3** (Scheme 5).[18]

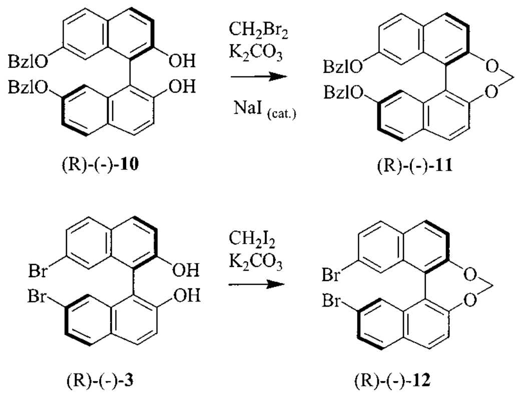
The CD spectrum (Figure 3) contains the negative couplet of compound (*R*)-**12** (in THF) in the region of the ^1B transition; the spectral characteristics of the exciton couplet for all compounds studied are reported in Table 1.

All the compounds investigated have an intense negative couplet at ca. 230 nm. For compounds with a dihedral angle θ smaller than the critical value, this spectral feature is indicative of the (*R*) configuration.[15]

A more detailed analysis of the CD spectra confirmed the reliability of this stereochemical assignment. In the absorption spectra of the cyclic derivatives **11** and **12**, the 230 nm band (which is due to the overlap of the two exciton components of the ^1B transition of each 2-naphthol monomer) has a high-energy exciton component that is shown to be more intense than the low-energy one. This observation



Scheme 4. Synthesis and resolution of (*R*)-(−)-7,7′-bis(benzyloxy)-2,2′-dihydroxy-1,1′-binaphthyl (**10**)



Scheme 5. Synthesis of (*R*)-(−)-**11** and (*R*)-(−)-**12**

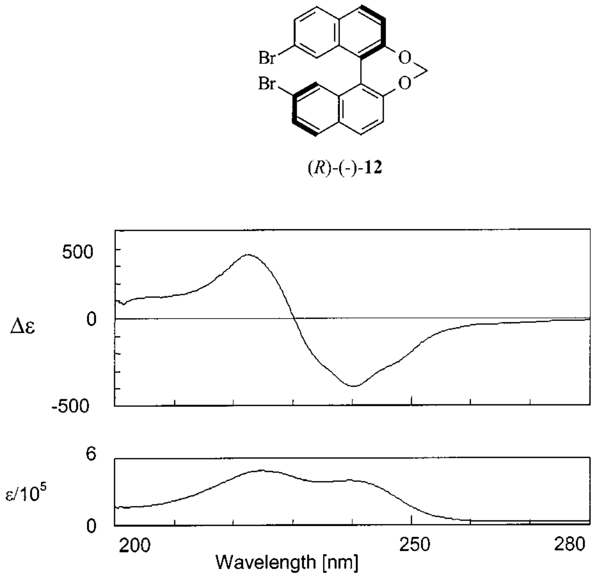


Figure 3. CD and absorption spectra of (*R*)-(−)-**12** in THF in the spectral region of the naphthalene ^1B_b electronic transition

Table 1. The helical twisting powers of derivatives (*R*)-**3**, **7**, **8**, **10−15** in the nematic phases E7 and MBBA, and the amplitude and sign of the exciton couplet (in THF) corresponding to the ^1B_b transition of the naphthalene

Compound	X	Y	β(E7)	β(MBBA)	$\Delta\Delta\varepsilon \times 10^{-2}$
11	Br	OCH_2O	−68	−80	−7.6
12	BzlO	OCH_2O	−80	−49	−6.7
13	H	OCH_2O	−85		
10	BzlO	OH	−5	−8	−5.7
3	Br	OH	+26.1	+18	−4.7
8	*p*-Tolyl	OH	+49.4.	+39.4	−1.1
14	H	OH	−32		
6	Br	OMe	+6.8	+4.2	−6.5
7	*p*-Tolyl	OMe	+80	+27.1	−1.3
15	H	OMe	−1.5	+3.8	

was also reported for other binaphthyl derivatives[19] that were shown by MM calculations to have dihedral angles not far from 60°.[20] The spectra of **3, 7, 8, 10** and **15** do not contain couplets, therefore θ of these non-bridged derivatives is certainly larger than 55° and near to the critical value.

To confirm the chiroptical assignment, we undertook the analysis of these chiral substances by employment of the LC technique (Figure 4). As is well known, this approach is based on the observation that the addition of an enantiomerically enriched chiral compound to nematic liquid crystals induces cholesteric mesophases. The cholesteric helix is characterised by its handedness and pitch. The ability of a chiral dopant to twist the nematic phase is expressed by the twisting power $\beta = (p\ c\ r)^{-1}$, where p is the pitch, c the concentration of the dopant (expressed as molar fraction) and r is its enantiomeric excess; the sign of β is positive for a right-handed cholesteric and is negative for a left-handed one. The phenomenon of cholesteric induction has been applied to configurational and conformational analysis. When both the solute and the nematic solvent have a biaryl structure, it is possible to correlate the helicity of the biaryl solute to the handedness of the induced cholesteric phase through a model based on the transfer of chirality from the dopant to the solvent by chiral conformation of the solvent molecule: therefore if the absolute configuration is known, the *s-cis* or *s-trans* conformation can be deduced and vice versa. For an *s-cis* conformation, a negative β-value indicates (*R*) absolute configuration.[17] Moreover, the absolute value of β is connected to the θ dihedral angle.[21]

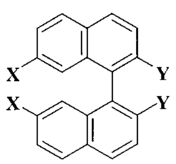


Figure 4. Substituted BINOLs tested in the chiroptical analysis

The twisting powers of the bridged and unbridged 7,7′-disubstituted-1,1′-binaphthyls measured in the biphenyl-type nematic solvent E7 and in MBBA are shown in Table 1. Inspection of the table gives rise to a few remarks: (i) The β values of compounds **11** and **12** (Scheme 5) are high and negative, similar to those reported for the parent[16] compound **13** and for other bridged 1,1′-binaphthyls.[17][22]

(ii) Non-bridged compounds show, instead, smaller twisting powers whose signs depend on the nature of the 7,7′-substitution and on the nematic solvent: this feature has been already described in literature[23] (e.g., **10** and **14**).

The model of chiral transfer presented above is based on the assumption that the molecular helicity along the biaryl axis is transferred to the nematic solvent. This hypothesis seems to be verified in the present system: for bridged compounds the value (and sign) of β is not much affected when the hydrogens in the 7,7′ position (**13**) are substituted with much bigger bromine atoms (**11**) or with bulkier benzyl groups (**12**). This substitution does not modify, in fact, the dihedral angle between the naphthyl moieties, which is mainly determined by the presence of the bridge between the 2 and 2′ positions.[24]

On the basis of the handedness of the cholesteric induced in nematic solvents, it was possible to assign *R* as the absolute configuration of the 7,7′ disubstituted binaphthyls (**3**, **6−8**, **11−12**).

Results in Catalysis

Investigation of the catalytic properties of metal−BINOL complexes, prepared from $Ti(OiPr)_2Cl_2$, $Zr(OiPr)_4$ or $ZrCl_4(THF)_2$ and the disubstituted BINOLs described above, was undertaken. Moreover, to rationalize the influence of the substituents of the aromatic rings on their catalytic activity, 3,3′ dibromobinaphthol **16**[25] and 6,6′ dibromobinaphthol **17**[26] were synthesized by following the known procedures. We chose, as a probe reaction, the addition of allyltributyltin to aldehydes as promoted by titanium or zirconium BINOL complexes, already developed in our laboratories.[27] Particularly, the addition of allyltributyltin to benzaldehyde, octyl aldehyde and cyclohexane carboxaldehyde was looked at (Scheme 6). The metal complexes were generated in situ by the use of our standard protocols, except for the Entries where $Ti(OiPr)_2Cl_2$ was used as precursor. In this case, the complex was generated by a two-step procedure (see the Experimental Section). We cannot suggest, at present, reasonable structures for all the complexes generated; spectroscopic studies failed to identify well-defined molecular structures of the catalysts and all attempts to grow crystals were unsuccessful.

The results obtained are collected in Table 2. A general trend is that dibromo- or ditolyl-substituted BINOL ligands **3**, **8**, **16**, **17** afford moderately enantioselective catalysts with any metal system, with ee values in the 54−73% range, independently of the position of the substituents. It is not clear, at present, if this effect is due to a change in the electronic properties of the binaphthyl moiety or if it is due to a different structure of the Lewis acid catalyst. A special case is represented by the combination of the hindered 3,3′-dibromobinaphthol **16** with $Zr(OiPr)_4$ which gives rise to an almost unselective catalyst (Entry 2), probably because of reduced availability of the catalytic site for steric reasons.

Different behaviour is shown by the dibenzyloxy derivative **10**. The catalyst formed from **10** and $Ti(OiPr)_2Cl_2$ proved to be superior to the parent BINOL catalyst in the allylation of benzaldehyde, in terms of both stereoselectivity and reaction rate (Entry 10). We believe that the strong electron-releasing properties of the alkoxy substituents can beneficially affect the performances of the catalysts prepared from **10**, but further investigation in this direction will occur.

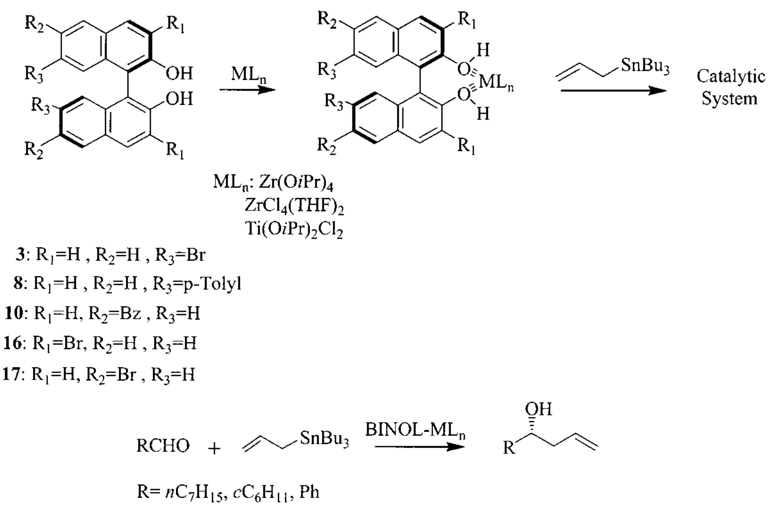
Conclusion

In summary, a simple, straightforward access to enantiomerically pure 7,7′-dibromo-BINOL (**3**), starting material for the preparation of a library of chiral 7,7′-disubstituted BINOLs, was described. The absolute configuration of the 7,7′-disubstitued binaphthyl was confirmed by the combined use of circular dichroism (exciton coupling approach) and liquid crystal (cholesteric induction) techniques. The dependence of the twisting powers on the nature of the substituents supports the hypothesis that the most important feature for the chiral information transfer between dopant and solvent is the dihedral angle between the aromatic planes. The effectiveness of various, differently substituted, BINOL ligands in the asymmetric allylation of aldehydes was investigated. The introduction of alkoxy substituents seems beneficial for the stereoselectivity of the titanium-based catalysts, while dibromo- or ditolyl-BINOLs afford less effective catalysts, especially if the 3,3′-positions are involved. Further work is in progress in our laboratories towards the rational design of alkyl- and aryl-substituted BINOL derivatives that can enhance the enantioselection in catalytic asymmetric reactions.

Experimental Section

General: ^1H- and ^{13}C-NMR spectra were recorded with a 300 MHz Varian Gemini instrument. Chemical shifts, δ, are given with respect to TMS and coupling constants, *J*, are measured in Hz. MS spectra were taken by EI ionization at 70 eV with a Hewlett-Packard 5971 with GC injection. They are reported as *m*/*z* (relative intensity in%). Column flash chromatography was run on 270−400 mesh silica gel. All the reactions were carried out in oven-dried glassware under nitrogen or argon. All the organic phases were dried with sodium sulfate. Hexane, toluene and THF were freshly distilled from Na−benzophenone ketyl. CH_2Cl_2 was distilled from P_2O_5. DMF was distilled from molecular sieves and stored under nitrogen over activated molecular sieves. Benzaldehyde, octyl aldehyde, and cyclohexane carboxaldehyde were distilled before use. All the other chemicals were commercially available and used as received. GC-MS analysis of chromatographated products showed that purity of 99% was achieved. Absorption and CD spectra were obtained by means of a JASCO J710 spectropolarimeter. Induced cholesteric pitch values were measured with the lens version of the Grandjean−Cano methods with a standard 16 Zeiss microscope. Helical handedness was obtained from the sign of the rotatory power. The enantiomeric excess was determined with as HPLC Chiralcel OD-H column.

7-Bromo-2-hydroxynaphthalene (2): To a stirred suspension of triphenylphosphane (18.3 g, 68.75 mmol.) in CH_3CN (3 mL) cooled at 0°C, bromine (3.52 mL, 68.75 mmol) was slowly added over



Scheme 6. Enantioselective allylation of aldehydes catalysed by chiral BINOL-metal complexes

Table 2. Enantioselective addition of allyltributyltin to aldehydes, catalysed by chiral BINOL−metal complexes[a]

Entry	BINOL	ML$_n$	Aldehyde	Yield (%)[b]	*ee* (%)[c]
1	**3**	Zr(O*i*Pr)$_4$	*n*-C$_7$H$_{15}$CHO	60	54
2	**16**	Zr(O*i*Pr)$_4$	*n*-C$_7$H$_{15}$CHO	65	14
3	**16**	Ti(O*i*Pr)$_2$Cl$_2$	*n*-C$_7$H$_{15}$CHO	70	72
4	**17**	Zr(O*i*Pr)$_4$	*n*-C$_7$H$_{15}$CHO	70	73
5	**17**	Zr(O*i*Pr)$_4$	*c*-C$_6$H$_{11}$CHO	62	70
6	**17**	Ti(O*i*Pr)$_2$Cl$_2$	*c*-C$_6$H$_{11}$CHO	60	72
7	**8**	ZrCl$_4$(THF)$_2$	PhCHO	43	60
8	**10**	Zr(O*i*Pr)$_4$	*n*-C$_7$H$_{15}$CHO	90	77
9	**10**	Zr(O*i*Pr)$_4$	*c*-C$_6$H$_{11}$CHO	50	66
10	**10**	Ti(O*i*Pr)$_2$Cl$_2$	PhCHO	80	92
11	**10**	ZrCl$_4$(THF)$_2$	PhCHO	56	75

[a] The allylation reactions were run in the optimal conditions based on the catalytic system used: (BINOL)Zr(O*i*Pr)$_4$ (20 mol-%), room temp.; (BINOL)ZrCl$_4$(THF)$_2$ (5 mol−%), −20 °C; (BINOL)-Ti(O*i*Pr)$_2$Cl$_2$ (20 mol-%), room temp. Details of the typical allylation procedure are provided (Entry 10) in the experimental section. − [b] All yields were determined on the pure isolated compounds after flash chromatography. − [c] Determined with a cyclodextrin Megadex5 chiral column. The absolute configuration of the isolated homoallylic alcohols was assigned by comparison of GC retention times with those of the known products.

30 min. After the addition, the mixture was warmed to room temperature and 2-hydroxynaphthalene **1** (11.01 g, 68.74 mmol) was added as one portion. The resulting mixture was heated at 80 °C for 2 h, then the solvent was removed by distillation. The dark residue obtained was heated at 250 °C for 6 h. The mixture was cooled to room temperature and then purified by chromatography on silica gel to give **2** as a pale yellow solid. − Yield: 5.4 g (35%). − M.p. 125 °C. ^{1}H NMR (CDCl$_3$): δ = 7.84 (d, 1 H, *J* = 2.0 Hz), 7.73 (d, 1 H, *J* = 8.8 Hz), 7.63 (d, 1 H, *J* = 8.7 Hz), 7.40 (dd, 1 H, *J* = 2.0, 8.7 Hz), 7.11 (dd, 1 H, *J* = 2.5, 8.8 Hz), 7.06 (d, 1 H, *J* = 2.5 Hz), 5.15 (br s, 1 H). − ^{13}C NMR (CDCl$_3$): δ = 155.16, 136.81, 130.96, 130.45, 129.38, 128.37, 128.08, 121.86, 119.22, 109.75. MS *m*/*z* (relative intensity) 224 (100), 222 (96), 195 (5), 143 (35), 115 (60). − HR MS for $C_{10}H_7Br_1O_1$: calcd. 221.9680260; found 221.9683388.

(±)-7,7′-Dibromo-2,2′-dihydroxy-1,1′-binaphthyl (3): A solution of **2** (20.96 g, 93.96 mmol) and CuCl$_2$ (25.6 g, 190.4 mmol) in degassed methanol (500 mL) was stirred under nitrogen for 15 min, then a solution of *tert*-butylamine (81 mL, 770 mmol) in methanol (320 mL) was added over a period of 2 h. After the resulting solution was stirred at room temperature for 24 h, the solution was cooled at 0 °C, then a 6 N solution of HCl was carefully added. The methanol was evaporated under reduced pressure and the residue was diluted with ethyl acetate (200 mL) and washed with brine (2 × 100 mL). The organic phase was separated, dried and concentrated under reduced pressure to give a residue which was then purified by flash chromatography (eluent cyclohexane/ethyl ether, 90:10). The solid was further purified by recrystallization from cyclohexane. − Yield: 19.7 g (94%). − M.p. 195−197 °C. − ^{1}H NMR (CDCl$_3$): δ = 7.96 (d, 2 H, *J* = 8.8 Hz), 7.78 (d, 2 H, *J* = 8.6 Hz), 7.48 (dd, 2 H, *J* = 1.6, 8.6 Hz), 7.39 (d, 2 H, *J* = 8.8 Hz), 7,24 (d, 2 H, *J* = 1.6 Hz), 5.12 (br s, 2 H). − ^{13}C NMR (CDCl$_3$): δ = 154.08, 135.15, 132.15, 130.64, 128.41, 128.21, 126.46, 122.91, 118.78, 110.15. − MS *m*/*z* (relative intensity): 444 (100), 442 (44), 284 (21), 256 (14), 226 (15), 222 (13), 142 (29), 119 (13), 113 (26), 43 (78). − HR MS for $C_{20}H_{12}Br_2O_2$: calcd. 441.9204020; found 441.9209941.

Resolution of (±)-7,7′-Dibromo-2,2′-dihydroxy-1,1′-binaphthyl (3). − Preparation of 4 and 5: To a stirred solution of (±)-**3** (10.75 g, 24.3 mmol) and (1*R*,2*S*,5*R*)-(−)-menthylchloroformate (10.9 mL, 50.8 mmol) in dry THF (100 mL), a solution of Et$_3$N (14.8 mL, 107 mmol) in THF (50 mL) was added under nitrogen. The resulting homogenous solution was stirred at room temperature for 4 h, then the THF was evaporated under reduced pressure and the residue was dissolved in CHCl$_3$ (25 mL). The solution was washed with a solution of 2 N HCl (5 mL) and brine, then the organic phase was separated, dried and concentrated under reduced pressure to give a solid. The solid was recrystallized three times from hexane affording the enantiomerically pure compound **4**. − Yield: 4.4 g (45%). − M.p. 201 °C. − ^{1}H NMR (CDCl$_3$): δ = 7.98 (d, 2 H, *J* = 8.7 Hz), 7.81 (d, 2 H, *J* = 8.9 Hz), 7.56 (dd, 2 H, *J* = 2.0, 8.7 Hz), 7.52 (d, 2 H, *J* = 8.9 Hz), 7.35 (d, 2 H, *J* = 2.0 Hz), 4.25 (m, 2 H), 1.9−0.2 (m, 36 H). − ^{13}C NMR (CDCl$_3$): δ = 153.54, 148.84, 135.25, 131.21, 131.15, 130.76, 130.60, 129.04, 123.10, 123.09, 122.75, 80.34, 47.63, 41.26, 34.94, 32.30, 27.06, 24.42, 22.98, 21.37, 17.14. − MS *m*/*z* (relative intensity): 808 (1), 764 (2), 626 (9), 488 (6), 444 (100), 364 (18), 284 (9), 255 (6), 226 (6), 139 (7), 95 (70), 83 (72), 69 (34), 55 (54), 41 (21). HR MS for $C_{42}H_{48}Br_2O_6$: calcd. 808.6456011; found 808.6450263. − $[\alpha]_D^{20}$ = −167.7 (*c* = 1.000, CHCl$_3$).

(*R*)-(−)-7,7′-Dibromo-2,2′-dihydroxy-1,1′-binaphthyl (3): To a solution of enantiopure **4** (3.4 g, 4.2 mmol) in dry THF (80 mL), was added $LiAlH_4$ (2.3 g, 60 mmol), in portions, over 1 h. After 2 h, the reaction was quenched by adding an aqueous solution of 3 N HCl (80 mL). After the evaporation of THF, the mixture was extracted with CH_2Cl_2 (3 × 50 mL). The organic phases were collected, dried and concentrated under reduced pressure to give a solid which was purified by flash chromatography (eluant cyclohexane/ethyl ether, 90:10). The solid was further purified by recrystallization from cyclohexane. The enantiomeric excess was determined to be 99.9% by HPLC analysis. The HPLC analysis was performed with a Chiralcel OD-H column [eluant *n*-hexane/*i*PrOH (92:8), flow rate of 0.5 mL/min, UV detection]. − $[\alpha]_D^{20} = -215.9$ ($c = 1.000$, $CHCl_3$).

(*R*)-(−)-7,7′-Dibromo-2,2′-dimethoxy-1,1′-binaphthyl (6): To a mixture of **3** (1 g, 2.25 mmol) and K_2CO_3 (1.6 g, 11.6 mmol) in acetone (50 mL), was added CH_3I (5 mL, 80 mmol). The stirring mixture was refluxed for 48 h, then cooled to room temperature and filtered through a pad of celite. The celite was washed twice with ethyl acetate. The organic phases were collected, washed with 2 N HCl (10 mL), dried, and concentrated under reduced pressure to give a solid which was purified by column chromatography (cyclohexane/ethyl acetate, 90:10). − Yield: 1.54 g (74%). − The solid was further purified by crystallization from cyclohexane:ethyl acetate. − M.p. 201−205 °C. − ^1H NMR ($CDCl_3$): $\delta = 7.96$ (d, 2 H, $J = 9.0$ Hz), 7.92 (d, 2 H, $J = 8.7$ Hz), 7.46 (d, 2 H, $J = 9.0$ Hz), 7.41 (d, 2 H, $J = 8.7$ Hz), 7,24 (d, 2 H, $J = 1.8$ Hz), 3.78 (s, 6 H). − ^{13}C NMR ($CDCl_3$): $\delta = 156.07$, 136.22, 130.82, 128.64, 128.11, 127.98, 122.25, 118.99, 115.23, 57.70. − MS; *m*/*z* (%): 472 (49), 470 (25), 394 (52), 392 (53), 348 (13), 346 (15), 314 (100), 268 (47). − HR MS for $C_{22}H_{16}Br_2O_2$: calcd. 469.9517021; found 469.9512293. − $[\alpha]_D^{20} = -187.2$ ($c = 1.000$, $CHCl_3$).

(*R*)-(−)-2,2′-Dimethoxy-7,7′-bis(4-methylphenyl)-1,1′-binaphthyl (7): A flask was flushed with nitrogen and charged with a mixture of **6** (0.4 g, 0.85 mmol), 4-methylphenyl boronic acid (0.3 g, 2.2 mmol), $Pd(PPh_3)_4$ (0.04 g, 0.035 mmol) and $Ba(OH)_2$ (0.92 g, 2.9 mmol), and then distilled DMF (10 mL) was added. The stirring mixture was refluxed for 20 h. The mixture was cooled to room temperature, then quenched by adding a saturated solution of NH_4Cl (5 mL). The DMF was evaporated under reduced pressure and the resulting mixture was extracted with CH_2Cl_2 (3 × 5 mL). The organic phases were collected, dried and concentrated under reduced pressure to give a residue which was then purified by flash chromatography (cyclohexane/ethyl acetate, 90:10). − Yield: 0.35 g (81%). − M.p. 166−168 °C. − ^1H NMR ($CDCl_3$): $\delta = 7.98$ (d, 2 H, $J = 8.8$ Hz), 7.92 (d, 2 H, $J = 8.5$ Hz), 7.56 (dd, 2 H, $J = 1.8$, 8.5 Hz), 7.46 (d, 2 H, $J = 8.8$ Hz), 7.33 (d, 2 H, $J = 1.8$ Hz), 7.29 (m, 4 H), 7.11 (m, 4 H), 3.79 (s, 6 H), 2.31 (s, 6 H). − ^{13}C NMR ($CDCl_3$): $\delta = 156.45$, 139.96, 139.81, 137.75, 135.37, 130.27, 130.20, 129.47, 129.40, 128.30, 124.46, 124.11, 115.22, 57.96, 21.99. − MS *m*/*z* (relative intensity): 494 (5), 406 (5), 405 (31), 404 (100), 359 (8), 358 (25), 315 (5), 314 (19), 268 (8). − HR MS for $C_{36}H_{30}O_2$: calcd. 494.22459050; found 494.2256939. − $[\alpha]_D^{20} = -294.7$ ($c = 1.000$, $CHCl_3$). − The enantiomeric excess (99.9%) was determined by HPLC analysis. The HPLC analysis was performed with a Chiracel OD-H column on the corresponing bis(*S*)-camphorsulfonate: eluant *n*-hexane/*i*PrOH (99:1), flow rate of 0.5 mL/min, UV detection.[29] (*R*)-(−)-(**7**): $t_r = 21.09$ min; (*S*)-(+)-(**7**): $t_r = 22.83$ min. − $[\alpha]_D^{20} = -294.7$ ($c = 1.000$, $CHCl_3$).

(*R*)-(−)-2,2′-Dihydroxy-7,7′-bis(4-methylphenyl)-1,1′-binaphthyl (8): To a solution of (*R*)-**7** (0.3 g, 0.61 mmol) in CH_2Cl_2 (40 mL) at 0 °C, BBr_3 (3.66 mL, 3.66 mmol) was added. The solution was allowed to warm to room temperature and stirred for 20 h. The excess of BBr_3 was decomposed by the dropwise addition of distilled water. The resulting mixture was diluted with water and extracted with CH_2Cl_2 (3 × 5 mL). The organic phases were collected, dried and concentrated under reduced pressure to afford the crude product which was then purified by flash chromatography (cyclohexane/ethyl ether, 90:10). Yield: 0.22 g (78%). − M.p. 181−183 °C. − ^1H NMR ($CDCl_3$): $\delta = 7.99$ (d, 2 H, $J = 8.8$ Hz), 7.96 (d, 2 H, $J = 8.7$ Hz), 7.63 (dd, 2 H, $J = 1.7$, 8.4 Hz), 7.39 (dd, 2 H, $J = 1.7$, 8.8 Hz), 7.36 (s, 2 H), 7.32 (d, 4 H, $J = 8.2$ Hz), 7.14 (d, 4 H, $J = 8.2$ Hz), 5.12 (br, 2 H), 2.31 (s, 6 H). − ^{13}C NMR ($CDCl_3$): $\delta = 154.22$, 141.41, 139.24, 138.24, 134.69, 132.25, 130.41, 129.97, 129.62, 128.39, 124.93, 122.84, 118.68, 112.02, 22.06. − MS; *m*/*z* (%): 466 (8), 377 (92), 376 (100), 205 (5), 179 (5), 32 (10). − HR MS for $C_{34}H_{26}O_2$: calcd. 466.1932803; found 466.1939969. − $[\alpha]_D^{20} = -390.4$ ($c = 1.000$, $CHCl_3$).

(*R*)-(−)-7,7′-Bis(benzyloxy)-2,2′-methylenedioxy-1,1′-binaphthalene (11): A mixture of (*R*)-(−)-**10** (0.05 g, 0.1 mmol), dibromomethane (0.021 mL, 0.3 mmol), K_2CO_3 (0.8 g, 0.5 mmol) and a catalytic amount of NaI were refluxed in dry acetone with stirring under nitrogen for 96 h. After cooling, the reaction mixture was poured into water and extracted with Et_2O (3 × 5 mL). The combined organic layers were washed with a 10% solution of NaOH (7 mL) and dried with K_2CO_3. The product was purified by flash chromatography (cyclohexane/ethyl ether, 70:30) and crystallized from heptane. − Yield: 0.015 g (29%). − ^1H NMR ($CDCl_3$): $\delta = 7.97$ (d, 2 H, $J = 8.7$ Hz), 7.40 (d, 2 H, $J = 8.7$ Hz), 7.30−6.96 (m, 14 H), 5.73 (s, 2 H), 4.73 (s, 4 H).

(*R*)-(−)-7,7′-Dibromo-2,2′-methylenedioxy-1,1′-binaphthalene (12): To a stirred mixture of (*R*)-(−)-**3** (0.06 g, 0.135 mmol) and anhydrous K_2CO_3 (0.041 g, 0.297 mmol) in DMF (2 mL), kept between 80−90 °C, methylene iodide (0.02 mL) was added. The reaction mixture was heated for an additional 48 h, then it was poured into water and extracted with ether. The organic layers were collected, washed with 5% NaOH (3 mL) and dried with K_2CO_3. The solvent was removed under reduced pressure and the product was purified by crystallization from hexane. − Yield: 0.016 g (26%). − ^1H NMR ($CDCl_3$): $\delta = 7.98$ (d, 2 H, $J = 8.7$ Hz); 7.83 (d, 2 H, $J = 8.7$ Hz); 7.66 (s, 2 H); 7.56 (d, 2 H, $J = 8.7$ Hz); 7.50 (d, 2 H, $J = 8.7$ Hz); 5.70 (s, 2 H).

Typical Procedure for the Catalytic Asymmetric Addition of Allyltributyltin to Aldehydes: A dried 25-mL flask was charged with 2 mL of CH_2Cl_2, 25 mg (0.05 mmol) of (*R*)-(−)-**10**, 100 µL (0.05 mmol) of $Ti(OiPr)_2Cl_2$ (0.5 M in toluene) and 31 µL (0.1 mmol) of allyltributyltin. The resulting homogeneous solution was stirred at room temperature for 1 h, then 26 µL (0.25 mmol) of freshly distilled benzaldehyde was added, followed by 155 µL (0.5 mmol) of allyltributyltin. The resulting brown solution was stirred for 1.5 h at room temperature. The reaction was then quenched by adding a saturated solution of $NaHCO_3$ (5 mL) and extracted with Et_2O (3 × 5 mL) and washed with brine (3 mL). The organic layers were collected, dried and concentrated under reduced pressure. Finally, the homoallylic alcohol was purified by flash chromatography (cyclohexane/ethyl ether, 80:20) affording the (*R*)-1-phenyl-3-buten-1-ol as a pale yellow oil in 92% ee. − Yield: 60 mg (80%).

Acknowledgments

We are grateful to Prof. Francesco Gasparrini (University of Rome) for providing the chiral HPLC analysis. We thank C.N.R., MURST (progetto Nazionale "Stereoselezione in Sintesi Organica, Metodologie ed Applicazioni"), MURST program "Liquid crystal: Structures, Computer Simulations, Properties and Applications", Cofin'97, and Bologna University (funds for selected research topics).

[1] [1a] K. Mikami, M. Tereda, T. Nakai, *J. Am.Chem. Soc.* **1990**, *112*, 3949−3954. − [1b] A. L. Costa, M. G. Piazza, E. Tagliavini, C. Trombini, A. Umani-Ronchi, *J. Am. Chem. Soc.* **1993**, *115*, 7001−7002. − [1c] G. E. Keck, K. H. Tarbet, L. S. Geraci, *J. Am. Chem. Soc.* **1993**, *115*, 8467−8468. − [1d] D. R. Gauthier Jr, E. M. Carreira, *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 2363−2365.

[2] C. Rosini, L. Franzini, A. Raffaelli, P. Salvadori, *Synthesis* **1992**, 503−517.

[3] S. Kobayashi, S. Komiyama, H. Ishitani, *Angew. Chem. Int. Ed.* **1998**, *37*, 979−981.

[4] M. Shibasaki, H. Sasai, T. Arai, *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 1236−1256.

[5] [5a] L. Ma, Q.-S. Hu, L. Pu, *Tetrahedron Asymmetry* **1996**, *7*, 3103−3106. − [5b] H. Cheng, L. Ma, Q.-S. Hu, X.-F. Zheng, J. Anderson, L. Pu, *Tetrahedron: Asymmetry* **1996**, *7*, 3083−3086. − [5c] Q.-S. Hu, W.-S. Huang, D. Vitharana, X.-F. Zheng, L. Pu, *J. Am. Chem. Soc.* **1997**, *119*, 12454−12464.

[6] [6a] Q-S. Hu, D. Vitharana, X.-F. Zheng, C. Wu, C. M. S. Kwan, L. Pu, *J. Org. Chem.* **1996**, *61*, 8370−8377. − [6b] Y. Meng, W. T. Slaven IV, D. Wang, T.-J. Liu, H.-F. Chow, C.-J. Li, *Tetrahedron: Asymmetry* **1998**, *9*, 3693−3707. − [6c] K. Onitsuka, Y. Harada, F. Takei, S. Takahashi, *Chem. Commun.* **1998**, 643−644.

[7] [7a] C.-J. Li, W. Slaven IV, V. T. John, S. Banerjee, *Chem. Commun.* **1997**, 1569−1570. − [7b] H.-J. Deussen, E. Hendrickx, C. Boutton, D. Krog, K. Clays, K. Bechegaard, A. Persoons, T. Bjørnholm, *J. Am. Chem. Soc.* **1996**, *118*, 6841−6852.

[8] H. Sasai, T. Tokunaga, S Watanabe, T. Suzuki, N. Itoh, M. Shibasaki, *J. Org. Chem.* **1995**, *60*, 7388−7389.

[9] [9a] J. Reeder, P. P. Castro, C. B. Knobler, E. Martinborough, L. Owens, F. Diederich, *J. Org. Chem.* **1994**, *59*, 3151−3160. − [9b] E. Martinborough, T. M. Denti, P. P. Castro, T. B. Wyman, C. B. Knobler, F. Diederich, *Helv. Chim. Acta* **1995**, *78*, 1037−1066. − [9c] M. R. Hester, M. A. Ueki, F. Diederich, *Israel J. Chem.* **1989**, *29*, 201−212.

[10] [10a] J. P. Schaefer, J. Higgins, P. K. Shenoy, *Org. Synth.* **1969**, *49*, 6−9. − [10b] G. Porzi, C. Concilio, *J. Organomet. Chem.* **1977**, *128*, 95−98.

[11] T. Igaki, K. Horisawa, M. Saito, T. Obitsu, M. Kinoshita, *Jpn. Kokai Tokyo Kono JP 63063753 A2*; *Chem. Abstr.* **1989**, *CA*, 31502J.

[12] M. Smrčina, J. Poláková, S. Vyskočil, P. Kočoský, *J. Org. Chem.* **1993**, *58*, 4534−4538.

[13] O. De Lucchi, D. Fabbri, G. Delogu, *J. Org. Chem.* **1995**, *60*, 6599−6601.

[14] T. Watanabe, N. Miyaura, A. Suzuki, *Synlett* **1992**, 207−210.

[15] [15a] S. F. Mason, R. H. Seal, D. R. Roberts, *Tetrahedron* **1974**, *30*, 1671−1682. − [15b] N. Harada, K. Nakanishi in *Circular Dichroic Spectroscopy − Exciton Coupling in Organic Stereochemistry*, Oxford, Oxford University Press, **1983**.

[16] C. Rosini, I. Rosati, G. P. Spada, *Chirality* **1995**, *7*, 353−358.

[17] G. P. Spada, G. Proni, *Enantiomer*, **1998**, *3*, 301−314 and references therein.

[18] J. E. Simpson, G. H. Daub, F. N. Hayes, *J. Org. Chem.* **1973**, *38*, 1771.

[19] [19a] M. Zhang, G. B. J. Schuster, *Phys. Chem.* **1992**, *96*, 3063−3067. − [19b] M. Zhang, G. J. B. Schuster, *J. Am. Chem. Soc.* **1994**, *116*, 4852−4857. − [19c] N. Kato, *J. Am. Chem. Soc.* **1990**, *112*, 254−257.

[20] This has been interpreted (N. Harada, H. Uda, *J. Chem. Soc., Chem. Commun.* **1982**, 230−232) to be connected to the amplitude of the dihedral angle: if we consider a binaphthyl compound with a θ far from the critical value, the two coupling modes will have overall transition moments with different moduli, and two different dipolar strengths will result. In particular, the high-energy component will carry a larger dipolar strength, as experimentally observed. When θ tends to the critical value, the difference between the moduli goes to zero.[16]

[21] The conformation of many bridged and non-bridged 1,1′-binaphthyl derivatives[16,17,22] has been related to the β-value: bridged compounds possess much higher twisting powers ($\beta = 50-100\ \mu m^{-1}$) than open derivatives (usually $\beta = 0-30\ \mu m^{-1}$). These high values can be rationalised on the basis of such compounds having a rigid structure, characterised by a dihedral angle θ around 50−55°. The correlation between the twisting power of binaphthyl derivatives and the aryl−aryl dihedral angle was confirmed by theoretical calculations:[23] the maximum absolute value of β is predicted for $\theta = \pm 45$ or ± 135.

[22] H. J. Deussen, P. V. Shibaev, R. Vinokur, T. Bjørnholm, K. Schaumburg, K. Bechgaard, *Liq. Cryst.* **1996**, *21*, 327−340.

[23] [23a] A. Ferrarini, G. J. Moro, P. L. Nordio, *Mol. Phys.* **1996**, *87*, 485−499. − [23b] A. Ferrarini, G. J. Moro, P. L. Nordio, *Phys. Rev.* **1996**, *56*, 681−688.

[24] On the other hand, in the non-bridged compounds the highest (and positive) value of β is observed for **7**, in which the tolyl groups are expected to force the *s-trans* conformation towards a dihedral angle not far from 135° (for which − in the unsubstituted binaphthyl − the maximum value of β is expected).[22] Moreover, β values of binaphthols are affected by the nature of the solvent to a lesser extent than in the methyl ethers: this observation is in agreement with the possibility of intramolecular H-bonds in **3**, **8**, **10** and **14** that reduce the conformational mobility around the aryl−aryl bond.[15]

[25] K. Maruoka, T. Itoh, Y. Araki, T. Shirasaka, H. Yamamoto, *Bull. Chem. Soc. Jpn.* **1988**, *61*, 2975−2976.

[26] K. Mikami, Y. Motoyama, M. Terada, *Inorg. Chim. Acta* **1994**, *222*, 71−75.

[27] [27a] P. Bedeschi, S. Casolari, A. L. Costa, E. Tagliavini, A. Umani-Ronchi, *Tetrahedron Lett.* **1995**, *36*, 7897−7900. − [27b] S. Casolari, P. G. Cozzi, P. Orioli, E. Tagliavini, A. Umani-Ronchi, *Chem. Commun.* **1997**, 2123−2124. − [27c] M. Bandini, P. G. Cozzi, A. Umani-Ronchi, *Chim. Ind. (Milan)* **1999**, *81*, 201−211.

[28] B. H. Lipschutz, B. James, S. Vance, I. Carrico, *Tetrahedron Lett.* **1997**, *38*, 753−756.

[29] H.-F. Chow, C.-W. Wan, M.-K. Ng, *J. Org. Chem.* **1996**, *61*, 8712−8714.

Received July 1, 1999
[O99388]