Optimization of New Chiral Ligands for the Copper-Catalysed Enantioselective Conjugate Addition of Et_2Zn to Nitroolefins by High-Throughput Screening of a Parallel Library

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A library of chiral ligands **5**, obtained with a modular building block strategy from the coupling of sulfonyl chlorides **1a–e**, amines **2f–j** and aldehydes **4p–t**, was screened in the enantioselective, copper-catalysed conjugate addition of Et_2Zn to aromatic and heteroaromatic nitroolefins **6a–e**. A multisubstrate high-throughput screening was realised by performing the addition reactions on an equimolar mixture of substrates **6c–d**. Good ligands for the addition reaction to nitroolefins **6a–e** (*ee*'s up to 58%) were identified.

Introduction

Enantioselective conjugate addition of organometallic reagents to prochiral Michael acceptors is an important method for C−C bond formation in organic synthesis.[1] Besides a number of stoichiometric reagents and chiral auxiliaries, some methods have recently been developed involving the use of catalytic quantities of chiral complexes.[1c] In particular, chiral copper complexes have proved very effective in the conjugate addition of dialkylzinc derivatives to cyclic and acyclic enones.[2,3]

Nitroolefins are readily accessible (by the Henry nitroaldol reaction),[4] powerful Michael acceptors[5] and the nitro group can be easily converted into other important functionalities (amines, aldehydes, etc.). However, reactions of nitroolefins with organometallics such as Grignard or organolithium reagents are not efficient and lead to a mixture of products arising from undesired side-reactions,[6] which can only partially be suppressed by carrying out the reactions at very low temperatures.[7] In 1995, Schäfer and Seebach[8] described an enantioselective (*ee* = 68−90%) conjugate addition of primary dialkylzinc reagents to 2-aryl and 2-heteroaryl nitroolefins mediated by stoichiometric quantities of titanium-TADDOLates. The copper-catalysed conjugate addition of diethylzinc to nitrostyrene was first reported by Alexakis in 1997.[9] The catalytic asymmetric version of this methodology was reported using copper complexes of Feringa's phosphoramidite ligands[10a] in the addition to simple nitroolefins[10b] and to cyclic nitrocarboxylate derivatives.[10c] While the results with the latter substrates were satisfactory (*ee*'s up to 92%),[10c] enantioselectivities with simple aromatic nitroolefins were only moderate (for example, *ee* = 48% for nitrostyrene).[10b] Very recently, while this paper was being submitted, Alexakis described in a preliminary communication the enantioselective Et_2Zn addition to nitroolefins in the presence of chiral catalysts with good *ee* values (60−94%).[11]

In this work we describe a combinatorial (parallel) approach to the optimization of chiral ligands for the copper-catalysed enantioselective conjugate addition of diethylzinc to 2-aryl and 2-heteroaryl nitroolefins. This approach consists of the high-throughput screening of a library of ligands (with the same structure and different substituents) for the identification of the most effective one.[12,13] We have recently reported a novel class of chiral Schiff-base ligands of general structure **5**.[12b] A library of 135 ligands was prepared in solution (with resin scavenging), and tested in the copper-catalysed enantioselective addition of diethylzinc to cyclic enones with enantiomeric excesses of up to 90%. The synthetic approach to these ligands consisted of the coupling of β-amino sulfonyl chlorides **1** with primary amines **2**. These sulfonyl chlorides were prepared in high yields from L-α-amino acids according to a straightforward synthetic protocol.[14] The *N*-Boc-β-amino sulfonamides **3** were then deprotected, and ligands **5** were obtained by condensation with the salicylaldehydes **4** (Scheme 1).

Results and Discussion

In order to explore the breadth of application of the ligands **5**, we studied the copper-catalysed conjugate addition of Et_2Zn to nitroolefins (Scheme 2). In preliminary experiments, a copper complex was preformed in situ by stirring

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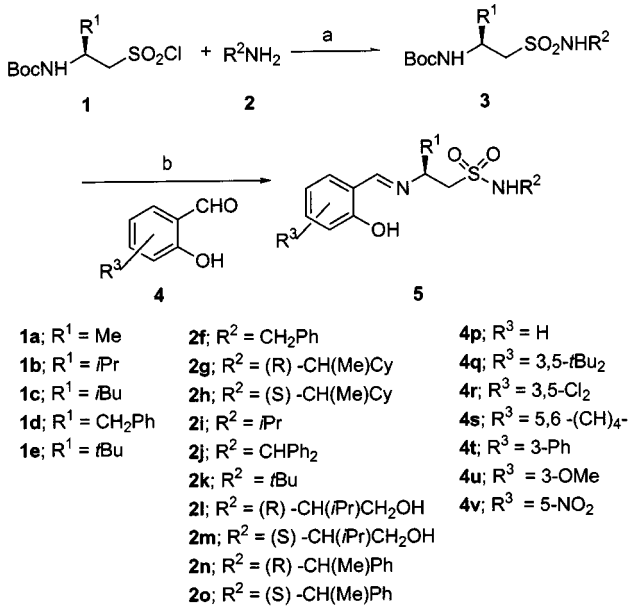
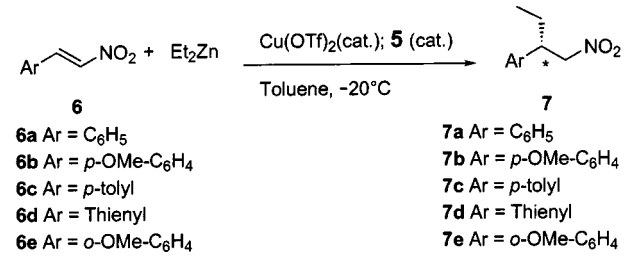


Scheme 1. Synthesis of the library of ligands **5**: a) **1** (1.2 equiv.), **2** (1.0 equiv.), methyl trimethylsilyl dimethylketene acetal [MTDA] (2.0 equiv.), polymer-bound "dimethylaminopyridine" (0.2 equiv.), CH_2Cl_2, 20 °C, 3 h; solid phase bound [tris(2-aminoethyl)amine] (3.0 equiv.), 3 h, 86%; b) **3** (1.0 equiv.), TFA/CH_2Cl_2 (1:3), 20 °C, 30 min; evaporation; **4** (0.9 equiv.), polymer-bound "dimethylaminopyridine" (3.0 equiv.), CH_3OH, 20 °C, 24 h, 88%

a catalytic amount of $Cu(OTf)_2$ (0.050 equiv.) in toluene in the presence of ligand **5dfp** (0.055 equiv.). The addition of diethylzinc (2.2 equiv.) and of nitroolefins **6** (1.0 equiv.) was then performed at −20 °C and the reaction stirred for 3 h before quenching. In these initial studies we chose the aromatic nitroolefins **6a−e** as candidate substrates. The enantiomeric excess of the reaction products was measured by injection of the crude reaction mixtures into a gas chromatograph (GC) equipped with a chiral capillary column. The conversion of the starting nitroolefins was good and the isolated yields of the reaction product were satisfactory (50−60%); unfortunately the enantiomeric excesses of these initial tests were consistently low (*ee* ≤ 10%) with ligand **5dfp**.



Scheme 2. Enantioselective conjugate addition of Et_2Zn to nitroolefins **6a−e** catalysed by $Cu(OTf)_2$/**5**; screening of the library of ligands **5**

A library of 125 different ligands, derived from the coupling of **1a−e**, **2f−j** and **4p−t** (Scheme 1), was then screened to improve the enantioselectivity. A multisubstrate screening[12,15] was also planned to optimize the ligand structure with respect to the different substrates. The nitroolefins **6c** and **6d** were chosen because the four GC peaks of the two enantiomeric pairs (reaction products **7c** and **7d**) did not overlap and gave baseline separation. The co-reaction was performed on an equimolar mixture of *p*-methylnitrostyrene and *trans*-2-(2-nitrovinyl)thiophene (**6c** and **6d**, 0.10 mmol each), using ligand **5** (5.5 mol-%, 0.011 mmol) and $Cu(OTf)_2$ (5 mol-%, 0.010 mmol) in toluene/hexane (4.5:1) at −20 °C. The reactions were quenched after 3 h, and the crude reaction mixtures were directly analysed for conversion and enantiomeric excess determination by chiral GC. The best 10 results of this screening for **6c** and **6d** are reported in Table 1.

Table 1. Screening of the library of ligands **5** in the addition of diethylzinc to nitroolefins **6c** and **6d**, best 10 results

Entry	L*	R^1	R^2	R^3	**7c** *ee* [%]	**7d** *ee*[%]
1	**5egt**	*t*Bu	(*R*)-CH(Me)Cy	3-Ph	52	36
2	**5ehr**	*t*Bu	(*S*)-CH(Me)Cy	3,5-Cl_2	51	37
3	**5dht**	CH_2Ph	(*S*)-CH(Me)Cy	3-Ph	50	34
4	**5ehs**	*t*Bu	(*S*)-CH(Me)Cy	5,6-$(CH)_4$	50	28
5	**5ejr**	*t*Bu	$CHPh_2$	3,5-Cl_2	46	33
6	**5bgt**	*i*Pr	(*R*)-CH(Me)Cy	3-Ph	45	30
7	**5djt**	CH_2Ph	$CHPh_2$	3-Ph	45	26
8	**5egr**	*t*Bu	(*R*)-CH(Me)Cy	3,5-Cl_2	43	32
9	**5ehq**	*t*Bu	(*S*)-CH(Me)Cy	3,5-*t*Bu_2	45	23
10	**5egs**	*t*Bu	(*R*)-CH(Me)Cy	5,6-$(CH)_4$	42	26

Analysis of the results of the library screening (Table 1; see Supporting Information for the complete layout) reveals some interesting features: i) addition to *p*-methylnitrostyrene is intrinsically more stereoselective than to *trans*-2-(2-nitrovinyl)thiophene; ii) in ligands **5**, the stereocentre bearing R^1 controls the absolute configuration of the reaction product, which is always *S* for **7c** and *R* for **7d** (vide infra), while the stereocentre on R^2 (when present) tunes the selectivity; iii) in the case of R^1, steric hindrance is important for determining good enantioselectivities (*t*Bu > *i*Pr ≈ CH_2Ph > *i*Bu > Me); iv) electronic effects, on the other hand, seem to overcome steric effects for salicylaldehyde substituents R^3 (3-Ph > 3,5-Cl_2 > naphthyl > 3,5-*t*Bu_2 > H).

The best results of the screening were confirmed on a preparative scale on the two substrates (**6c** and **6d**) separately. Optimization of the reaction parameters (temperature, solvent, metal source, ligand-to-metal ratio) was then performed on **6c** to improve the enantioselectivity; the results are summarized in Table 2.

The results of this Table deserve some comments: i) increasing the ligand-to-metal ratio does not seem to affect the enantiomeric excesses (entries 2−3 vs. entry 1); ii) the use of Et_2Zn in toluene instead of Et_2Zn in hexane (entry 4 vs. entry 1) leads to a significant increase in conversion, possibly due to enhanced solubility of the reagents; iii) as for the metal source: copper(I) triflate gave slightly better results than copper(II) triflate (entries 7 vs. 4), whereas copper(I) cyanide and other metals [such as $Ni(acac)_2$] dramatically decreased conversion rates and enantioselectivities (entries 5 and 6 vs. entry 7); iv) as for the role of the solvent and additives: similar results were obtained when the reaction was performed in toluene or in DCM/hexane (entries

Table 2. Optimization for **6c**; tuning of the reaction parameters: ligand-to-metal ratio, metal source, temperature, solvent

Entry	L* (**5egt**)	M (5%)	Temp. (°C)	Solvent	*ee* (%)	Conv. (%)
1	5.5%	$Cu(OTf)_2$	−20	tol./hex.[a]	52	77
2	10%	$Cu(OTf)_2$	−20	tol./hex.[a]	51	80
3	7.5%	$Cu(OTf)_2$	−20	tol./hex.[a]	50	80
4	5.5%	$Cu(OTf)_2$	−20	toluene[b]	52	>98
5	*5.5%*	$Ni(Acac)_2$	−20	toluene[b]	0	25
6	*5.5%*	CuCN	−20	toluene[b]	0	50
7	5.5%	$[Cu(OTf)]_2$	−20	toluene[b]	54	>98
8	5.5%	$[Cu(OTf)]_2$	−20	DCM/hex.[a]	52	>98
9	5.5%	$[Cu(OTf)]_2$	−20	CH_3CN/tol.[b]	Nd[d]	<5
10	5.5%	$[Cu(OTf)]_2$	−20	toluene[b],[c]	Nd[d]	<5
11	5.5%	$[Cu(OTf)]_2$	−45	toluene[b]	48	>98
12	5.5%	$[Cu(OTf)]_2$	+10	toluene[b]	51	>98

[a] Et_2Zn 1.0 M in hexanes. − [b] Et_2Zn 1.1 M in toluene. − [c] 2.0 Equiv. of methanol. − [d] Not determined.

8 vs. 7) but no reaction occurred when CH_3CN was employed or if two equivalents of methanol were added; v) as for the temperature: surprisingly, a slight decrease of enantioselectivity was observed when the reaction was conducted at lower temperature (entries 11 vs. 7) and similar enantioselectivity was obtained at +10 °C (entries 12 vs. 7).

The best reaction conditions (5.5% of the ligand, 5.0% of $[Cu(OTf)]_2{\cdot}C_6H_6$, toluene, −20 °C) were then applied to the different substrates **6a−6e** using the two best ligands resulting from the screening of the library (**5ehr** and **5egt**). The results are summarized in Table 3.

Table 3. Enantiomeric excesses observed under the best reaction conditions for the addition of Et_2Zn to nitroolefins **6a−6e** with ligands **5ehr** and **5egt**

Entry	Nitroolefin	Product	% *ee* (with **5ehr**)	% *ee* (with **5egt**)
1	**6a**	**7a**	58	54
2	**6b**	**7b**	44	38
3	**6c**	**7c**	57	54
4	**6d**	**7d**	41	33
5	**6e**	**7e**	42	32

The enantioselectivities of the products **7a−e** are moderate and consistent. Slightly better results (41 to 58%) were observed with ligand **5ehr** than with ligand **5egt** (32 to 54%). Conversions of the 2-aryl and 2-heteroaryl nitroalkanes were complete (≥98%), and the products **7a−7e** were obtained in satisfactory isolated yield (55−68%; see Experimental Section). The absolute configuration of the major enantiomers of products **7a−e** was assigned according to the procedure described by Seebach and Schäfer for the determination of the facial selectivity of the Et_2Zn addition to constitutionally similar nitroalkanes.[8] In particular, the absolute configurations of **7a**, **7b**, and **7d**, used also by Seebach and Schäfer, were assigned by comparison with the reported optical rotations,[8] and were *S* for **7a** and **7b**, and *R* for **7d**. For **7c** and **7e**, the configuration was assumed to be *S* following Seebach's procedure. From these results, we assign all our major products as resulting from *Si*-face addition to the nitroolefins.

Conclusion

In conclusion, we have realised a copper-catalysed enantioselective conjugate addition of diethylzinc to 2-aryl and 2-heteroaryl nitroolefins. Good conversions and acceptable enantioselectivities were observed. These results confirm the value of the "combinatorial approach": it would have been very difficult to identify these ligands if a "rational" or a "positional scanning"[16] approach were followed. In addition, the data in Table 1 clearly show the importance of the mutual influences of the different substituents (R^1, R^2, R^3) in the fine tuning of the ligand structure.

Experimental Section

General Remarks: Solvents were purified according to standard procedures. Ligands **5** were synthesised according to previously reported procedures[12]. $Cu(OTf)_2$, $[Cu(OTf)]_2{\cdot}C_6H_6$, Et_2Zn (1.0 M solution in hexanes), Et_2Zn (1.1 M solution in toluene) and nitroolefins **6a−6d** were purchased from Aldrich or Fluka AG. Nitroolefin **6e** was synthesized according to a literature procedure.[17] The enantiomeric excesses were determined by injection into a GC instrument equipped with a chiral capillary column (column: MEGADEX DMEPEβ, 25 m, film 0.25 μm).

General Procedure for the Screening of the Library: In a flame-dried flask, under argon atmosphere, compound **5** (0.011 mmol) was dissolved in dry toluene (1 mL). $Cu(OTf)_2$ (3.6 mg; 0.01 mmol) was added and the resulting brownish solution was stirred at ambient temperature for 30 min. The reaction mixture was then cooled to −20 °C and Et_2Zn (1.0 M solution in hexanes; 0.44 mL, 0.44 mmol) and a solution of a 1:1 mixture of **6c** and **6d** (17 mg and 16 mg, respectively, 0.1 mmol each, 0.2 mmol total) in dry toluene (1 mL) were consecutively added. The reaction mixture was stirred at −20 °C for 3 h, quenched with saturated aqueous NH_4Cl (1 mL) and diluted with diethyl ether (1 mL). The organic phase was separated and filtered through celite. The crude reaction mixture (1 μL) was then injected into the GC instrument (carrier H_2 1.8 bar; injector: 200 °C; detector: 200 °C; oven temperature: 90 °C, 1 °C/min to 200 °C; t_R (**7d**): 26.4 min and 26.9 min; t_R (**7c**): 33.8 min and 34.1 min; t_R (**6d**): 37.6 min; t_R (**6c**): 44.4 min).

Optimized Reactions Conditions

2-(4-Methylphenyl)nitrobutane (7c): In a flame-dried flask, under argon atmosphere, **5ehr** (0.033 mmol) was dissolved in dry toluene (3 mL). $[Cu(OTf)]_2{\cdot}C_6H_6$, (7.5 mg; 0.03 mmol) was added and the resulting brownish solution was stirred at ambient temperature for 30 min. The reaction mixture was then cooled to −20 °C and Et_2Zn (1.1 M solution in Toluene; 1.20 mL, 1.31 mmol) and a solution of **6c** (100 mg, 0.6 mmol total) in dry toluene (3 mL) were consecutively added. The reaction mixture was stirred at −20 °C for 3 h and then quenched with saturated aqueous NH_4Cl (3 mL) and diluted with diethyl ether (3 mL). The organic phase was separated and filtered through celite. The reaction crude was purified by silica gel chromatography (hexane/ethyl acetate, 98:2) giving the Michael adduct **7c** with 100% conversion and 66% yield in 57% *ee* (carrier H_2 1.8 bar; injector: 200 °C; detector: 200 °C; oven temperature: 90 °C, 1 °C/min to 200 °C ; t_R (**7c**): 33.8 min and 34.1 min ; t_R (**6c**): 44.4 min). − ^{1}H NMR (200 MHz, $CDCl_3$): δ = 0.86 (t, J = 7.3, 3 H), 1.59−1.81 (m, 2 H), 2.34 (s, 3 H), 3.31−3.38 (m, 1 H), 4.53−4.65 (m, 2 H), 7.06−7.10 (m, 2 H), 7.15 −7.19 (m, 2 H). − ^{13}C NMR (50 MHz, $CDCl_3$): δ = 11.5 (q), 21.0 (q), 26.1 (t), 45.6 (d), 80.8 (t), 127.4 (d), 129.5 (d), 136.0 (s), 137.0 (s). − MS (EI): m/z = 193 [M^+], 146 [M^+ − HNO_2]. − IR (neat): $\tilde{\nu}$ = 1553 (s), 1380 (s) cm^{-1}. − $[\alpha]_D^{25}$ = −11.0 (c = 1.00, $CHCl_3$).

2-Phenylnitrobutane (7a): According to the procedure described above for **7c**, the Michael adduct **7a** was obtained with 100% conversion and 55% yield in 58% *ee* [carrier H_2 1.8 Bar; injector: 200 °C; detector: 200 °C; oven temperature: 100 °C, 1 °C/min to 200 °C t_R (**7a**): 19.9 min and 20.4 min; t_R (**6a**): 28.3 min]. Spectral data (^{1}H NMR, ^{13}C NMR, IR, MS) were identical to literature data.[8] $[\alpha]_D^{25}$ = −10.1 (c = 1.10, $CHCl_3$).

2-(4-Methoxyphenyl)nitrobutane (7b): According to the procedure described above for **7c**, the Michael adduct **7b** was obtained with 100% conversion and 68% yield in 44% *ee* [carrier H_2 1.0 Bar; injector: 200 °C; detector: 200 °C, oven temperature 100 °C, 0.5 °C/min to 200 °C; t_R (**7b**): 78.2 min and 78.7 min; t_R (**6b**): 103 min]. Spectral data (^{1}H NMR, ^{13}C NMR, IR, MS) were identical to literature data.[8] $[\alpha]_D^{25}$ = −15.1 (c = 0.96, $CHCl_3$).

2-(2-Thienyl)nitrobutane (7d): According to the procedure described above for **7c**, the Michael adduct **7d** was obtained with 100% conversion and 55% yield in 41% *ee* [carrier H_2 1.8 Bar; injector: 200 °C; detector: 200 °C; oven temperature: 90 °C, 1 °C/min to 200 °C t_R (**7d**): 26.4 min and 26.9 min; t_R (**6d**): 37.6 min]. Spectral data (^{1}H NMR, ^{13}C NMR, IR, MS) were identical to literature data.[8] $[\alpha]_D^{25}$ = −13.7 (c = 1.01, $CHCl_3$).

2-(2-Methoxyphenyl)nitrobutane (7e): According to the procedure described above for **7c**, the Michael adduct **7e** was obtained with 98% conversion and 67% yield in 42% *ee* [carrier H_2 1.6 Bar; injector: 200 °C; detector: 200 °C, oven temperature 110 °C, 1 °C/min to 200 °C; t_R (**7e**): 25.8 min and 26.6 min; t_R (**6e**): 41.1 min]. − ^{1}H NMR (200 MHz, $CDCl_3$): δ = 0.85 (t, J = 7.3, 3 H), 1.75−1.85 (m, 2 H), 3.64−3.78 (m, 1 H), 3.85 (s, 3 H), 4.55−4.69 (m, 2 H), 6.88−6.97 (m, 2 H), 7.09−7.15 (m, 1 H), 7.22−7.28 (m, 1 H). − ^{13}C NMR (50 MHz, $CDCl_3$): δ = 11.6 (q), 24.3 (t), 41.0 (d), 55.2 (q), 79.3 (t), 110.9 (d), 120.6 (d), 126.9 (s), 128.4 (d), 128.8 (d), 157.4 (s). − MS (EI): m/z = 209 [M^+], 162 [M^+ − HNO_2]. − IR (neat): $\tilde{\nu}$ = 1552 (s), 1380 (m), 1246 (s) cm^{-1}. − $[\alpha]_D^{25}$ = −4.0 (c = 1, $CHCl_3$).

Acknowledgments

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