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(2*S*,5*R*)-2-Methylaminomethyl-1-methyl-5-phenylpyrrolidine, a chiral diamine ligand for copper(II)-catalysed Henry reactions with superb enantiocontrol†

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A *cis*-2-aminomethyl-5-phenylpyrrolidine, which is easily available from methyl Boc-L-pyroglutamate, was found to be a highly efficient chiral ligand for Cu(II)-catalysed Henry reactions. Excellent yields (>90%) and superb levels of enantiocontrol (98.5–99.6% ee) were reached with aromatic, heteroaromatic, vinylic, and aliphatic aldehydes (36 examples).

The Henry (or nitroaldol) reaction is a powerful tool for C–C bond formation, because it permits rapid access to valuable synthetic intermediates such as 1,2-amino alcohols and α-hydroxy acids.[1] Tremendous advances have been made over the last two decades in the development of enantioselective versions of this reaction.[2] Among the many highly efficient systems based on heterobimetal,[3] transition metal,[4–6] organo[7] and enzyme[8] catalysis, chirally modified copper complexes have received particular attention due to the wide structural variability of the ligands (diamines, amino alcohols, amino imines, amino pyridines, imino pyridines, Schiff bases, box-type ligands, salen-type ligands, and others),[5,6] the ease of preparation and the, in part, high levels of stereocontrol reached. Several of these catalysts permit 99% ee in the addition of nitromethane to some of the aldehydes tested,[5] but none is capable of providing 99% ee for the majority of substrates. Herein we present the first copper catalyst that fulfils this demand, giving, for the addition of nitromethane to a broad range of aldehydes, the corresponding ß-nitro alcohols in high yield and excellent 99% ee.

In the course of our studies on bicyclic diamines[9] we became interested in 2-aminomethylpyrrolidines of general type **1** (Fig. 1), which carry an additional *cis*-aryl group in 5-position, as compared to proline derived diamines. Chelation of a metal with **1** will lead to a rigid bicyclic system, in which the aryl substituent is forced into an *endo*-position directly on top of the active metal site.

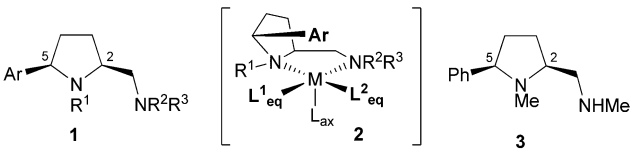


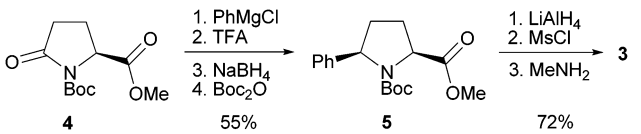
Fig. 1 *cis*-2-Aminomethyl-5-arylpyrrolidines **1** and **3** and a square-pyramidal metal complex of **1**, **2**.

As illustrated by complex **2**, such a shielding might be of particular importance in asymmetric transition metal catalysts preferring Jahn–Teller distorted octahedral geometries, because it selectively blocks one apical position and thereby reduces the number of possible transition states. The equatorial coordination sites L^1_{eq} and L^2_{eq} are still differentiated by the intrinsic steric and electronic properties of the C_1-symmetric diamine **1**, which might offer another advantage over C_2-symmetric ligands.

Copper(II)-catalysed Henry reactions, which are supposed to proceed *via* such a pentacoordinate intermediate,[10] might provide an ideal test system to probe the potential of the diamines **1**.[11] After investigating some derivatives, we quickly identified the simple compound **3** as the ligand of choice for these reactions.[12]

Diamine **3** is easily accessible from commercially available methyl Boc-L-pyroglutamate (**4**, Scheme 1). Treatment of **4** with phenylmagnesium chloride and re-cyclisation of the resulting, ring-opened ketone delivered the diastereomerically pure pyrrolidine **5** after crystallization.[13] Exhaustive reduction followed by OH/NHMe exchange afforded the target molecule **3** in overall seven simple steps and 40% yield.

The enantioselective Henry reactions between the aromatic aldehydes **6a–u** and nitromethane (11 equivalents) were performed on a 1 mmol scale in THF at −25 °C (Table 1, entries 1–21).



Scheme 1 Synthesis of diamine **3** from pyroglutamate **4**.

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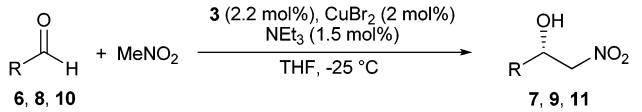
The copper(II) complex [**3**·$CuBr_2$], prepared prior to use by stirring $CuBr_2$ with a slight excess of pyrrolidine **3** in THF, was used as the chiral catalyst and NEt_3 (1.5 mol%) as the base. Under these conditions[12] and in the presence of just 2 mol% [**3**·$CuBr_2$], the Henry products **7a–u** were formed within 18 to 67 h in excellent 92–99% yield. Outstanding 99% ee, in several cases even more than 99.5% ee, were obtained with electronically more or less neutral (**6a–g**), electron-deficient (**6h–o**) and electron-rich (**6p–u**) aromatic aldehydes, carrying substituents in *ortho*-, *meta*-, or *para*-position.

Hetarylic aldehydes **8a–f** were also treated with nitromethane under these conditions (Table 1, entries 22–27). And again, the Henry products **9a–f** were obtained in excellent yields (90–99%) and superb >99.0% ee, irrespective of the heterocycle (furyl, thiophenyl, or NBoc-pyrryl) and the substitution pattern.

The α,β-unsaturated aldehydes **10a** and **10b** solely afforded the 1,2-addition products **11a** and **11b**. The latter one is the only compound tested within this context that delivered less than 99.0% ee, namely 98.7%.

In all cases, the *re*-face of the aldehyde was attacked by the nitronate; the, in part, opposite absolute stereo descriptors in the products are a formal consequence of the CIP-notation.

Table 1 Aromatic, heteroaromatic and vinylic aldehyde scope[a]



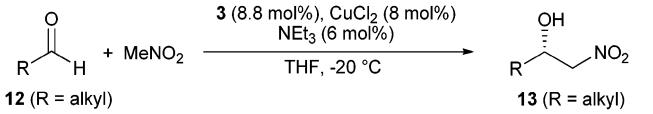
Entry	Compounds	R	Time (h)	Yield[b] (%)	ee[c] (%) (config.)
1	**6a, 7a**	Ph	24	92	99.3 (*S*)
2	**6b, 7b**	2-Me-Ph	18	99	99.2 (*S*)
3	**6c, 7c**	3-Me-Ph	20	99	99.5 (*S*)
4	**6d, 7d**	4-Me-Ph	22	93	99.4 (*S*)
5	**6e, 7e**	4-Ph-Ph	38	99	99.6 (*S*)
6	**6f, 7f**	1-Naphthyl	65	99	99.4 (*S*)
7	**6g, 7g**	2-Naphthyl	42	99	99.0 (*S*)
8	**6h, 7h**	2-O_2N-Ph	20	97	99.0 (*S*)
9	**6i, 7i**	3-O_2N-Ph	22	95	99.4 (*S*)
10	**6j, 7j**	4-O_2N-Ph	21	94	99.4 (*S*)
11	**6k, 7k**	2-Cl-Ph	18	99	99.6 (*S*)
12	**6l, 7l**	3-Cl-Ph	19	96	99.5 (*S*)
13	**6m, 7m**	4-Cl-Ph	42	95	99.5 (*S*)
14	**6n, 7n**	4-F-Ph	20	99	99.6 (*S*)
15	**6o, 7o**	4-NC-Ph	21	94	99.6 (*S*)
16	**6p, 7p**	2-MeO-Ph	42	97	99.5 (*S*)
17	**6q, 7q**	3-MeO-Ph	48	99	99.3 (*S*)
18	**6r, 7r**	4-MeO-Ph	67	99	99.2 (*S*)
19	**6s, 7s**	2,4-$(MeO)_2$-Ph	48	98	99.3 (*S*)
20	**6t, 7t**	2,5-$(MeO)_2$-Ph	39	99	99.6 (*S*)
21	**6u, 7u**	3,4-$(MeO)_2$-Ph	40	93	99.1 (*S*)
22	**8a, 9a**	2-Furyl	40	91	99.6 (*R*)
23	**8b, 9b**	5-Me-2-furyl	112	96	99.5 (*R*)[d]
24	**8c, 9c**	3-Furyl	72	99	99.4 (*S*)
25	**8d, 9d**	2-Thiophenyl	86	95	99.2 (*R*)
26	**8e, 9e**	NBoc-2-pyrryl	21	99	99.5 (*R*)
27	**8f, 9f**	NBoc-3-indolyl	160	90	99.4 (*S*)
28	**10a, 11a**	(*E*)-PhCH=CH	120	90	99.3 (*S*)
29	**10b, 11b**	(*E*)-1-Penten-1-yl	90	97	98.7 (*S*)[d]

[a] Performed on a 1 mmol scale in THF (600 μL) and $MeNO_2$ (600 μL ≈ 11 eq.). [b] Isolated yield. [c] Determined by HPLC analysis on a chiral phase; absolute configurations were established by comparison with literature data. [d] Absolute configuration was assigned based on a *re*-face attack on the aldehyde.

Aliphatic aldehydes **12** provided significantly lower enantioselectivities and yields under these conditions. Nonanal (**12b**), for example, delivered the Henry product **13b** in unsatisfying 53% yield and 94.5% ee after 40 h. In order to compensate the lower reactivity, we raised the amount of catalyst to 8 mol% and the temperature to −20 °C, which afforded **13b** in good 86% yield, but low 92.1% ee. Finally, a significant increase in the level of chirality transfer was observed by changing the copper salt from $CuBr_2$ to $CuCl_2$.[14] Under these modified conditions, both, linear (**12a–c**) and α-branched (**12d–g**) aliphatic aldehydes provided the Henry products **13a–g** in excellent 98.5–99.5% ee and >95% yield (Table 2).

The stereochemical outcome of the Henry reactions can be explained *via* the transition state **14** (Fig. 2). As mentioned earlier, the aryl group of the chiral ligand **3** blocks the upper apical position at the Cu(II) ion, thus leaving three open coordination sites, two equatorial ones and one apical one. Based on the known model,[10] the nitronate should bind apically for maximum activation, since its negative charge is less stabilised in this position by the copper ion. Of the two higher Lewis-acidic equatorial sites, the aldehyde should coordinate to the one next to the pyrrolidine moiety for two reasons: (i) this allows the sterically more demanding counter ion X to occupy the less congested position next to the aminomethyl group[9b] and (ii) with the weaker electron donating secondary amine opposite, the electrophilicity of the carbonyl group is increased thus facilitating a nucleophilic attack. Furthermore, the aldehyde must be oriented inwards in order to avoid severe steric repulsions with the chiral backbone. The C–C bond formation will presumably proceed *via* a six-membered,

Table 2 Aliphatic aldehyde scope[a]



Entry	Compounds	R	Time (h)	Yield[b] (%)	ee[c] (%) (config.)
1	**12a, 13a**	*n*Bu	40	95	98.5 (*S*)
2	**12b, 13b**	*n*Oct	60	97	98.6 (*S*)
3	**12c, 13c**	$PhCH_2CH_2$	40	95	99.5 (*S*)
4	**12d, 13d**	iPr	44	96	99.1 (*S*)
5	**12e, 13e**	*c*Pent	44	99	98.9 (*S*)
6	**12f, 13f**	*c*Hex	44	99	99.4 (*S*)
7	**12g, 13g**	*t*Bu	44	99	98.6 (*S*)

[a] Performed on a 1 mmol scale in THF (600 μL) and $MeNO_2$ (600 μL ≈ 11 eq.). [b] Isolated yield. [c] Determined by HPLC analysis on a chiral phase; absolute configurations were established by comparison with literature data.

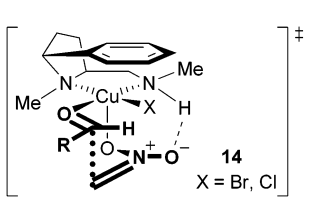


Fig. 2 Proposed transition state **14**.

chair-shaped transition state, thus obviating repulsions between the nitronate-oxygen and the pyrrolidine *N*-methyl group.[15] It might be possible that this arrangement receives some further stabilisation and rigidness by an intramolecular hydrogen bridge between the nitronate oxygen and the NH-proton of the chiral ligand. Thus, the steric and electronic properties of the diamine ligand apparently create close to perfect preconditions for the experimentally observed, almost exclusive *re*-face attack of the nitronate on the aldehyde carbonyl group.

In summary, the *cis*-5-phenyl substituted 2-aminomethyl-pyrrolidine **3**, which is accessible in just a few steps from methyl Boc-L-pyroglutamate (**4**), was successfully utilized as the chiral ligand in $CuBr_2$- and $CuCl_2$-catalysed Henry reactions. Excellent isolated yields (>90%) and superb enantioselectivities (98.5–99.6% ee) were obtained with a wide variety of aromatic, heteroaromatic, vinylic and aliphatic aldehydes (36 examples). Further studies are ongoing.[16]

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14 A similar effect on the ee was not observed with aromatic aldehydes.

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