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Indirect and direct catalytic asymmetric reductive amination of 2-tetralone

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Dedicated to Professor Henri Kagan on the occasion of his 80th birthday

ABSTRACT

Herein we report a one-pot catalytic asymmetric reductive amination of 2-tetralone. High-throughput screening of a small library of chiral ligands allowed us to perform the enantioselective hydrogenation of the intermediate enamine with up to 60% ee and a one-pot reaction with up to 47% enantiomeric excess of the desired amine.

1. Introduction

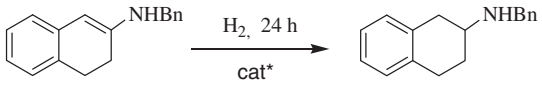
Today, many chemicals, which are used as specialities or in a large-scale market, have to be produced as enantiomerically pure compounds, such as pharmaceuticals, agrochemicals, flavours and fragrances. It is essential for chemists to discover direct and clean routes with a limited number of steps to produce enantiomerically pure molecules from simple and commercially available compounds. Furthermore, atom economy and highly selective reactions, which minimize waste and energy consumption, are among the most important goals in the field of Green Chemistry. The 2001 Nobel Prize to Noyori and Knowles represents a reward to their contribution in the field of enantioselective hydrogenation. Nevertheless, despite the impressive amount of knowledge achieved from their work, many challenges still remain.[1]

The enantioselective reductive amination of ketones in a one-pot reaction without isolation of the intermediates by using multi-functional catalysts remains a challenge of high importance. Such transformation, known in its non-asymmetric version, is performed under drastic heterogeneous conditions, which are not tolerated for the fine chemicals chemistry.[2] More convenient strategies based on mild reaction conditions are very rare and have been successfully used in only a few cases: by using the rhodium-catalyzed asymmetric reductive amination of α-keto-acids,[3] the titanium + iridium-catalyzed reductive amination of arylketones,[4] the ruthenium-catalyzed enantioselective reductive amination of β-ketoesters,[5] the ruthenium-catalyzed enantioselective hydrogen-transfer reductive amination of ketones,[6] the palladium-catalyzed asymmetric reductive amination of ketones[7] and the enantioselective organocatalytic reductive amination of ketones.[8]

Our interest was aimed at the production of optically active cyclic amines and enamines, because they are intermediates or models for biologically active compounds.[9] Simple enamines without chelating groups are challenging substrates,[10] since they do not need subsequent deprotection. Herein we report our studies concerning the catalytic asymmetric reductive amination of 2-tetralone.

2. Results and discussion

An ideal catalyst for our purpose should be able to promote the condensation of an amine with a ketone and also catalyze the enantioselective hydrogenation of the resulting prochiral unsaturated intermediate to produce enantiomerically pure amines. In order to find a suitable catalytic system, which allowed us to performing the enantioselective hydrogenation of the intermediate compound in the second step with high enantioselectivity the model compound benzyl-(3,4-dihydronaphthalen-2-yl)-amine was selected. This compound presents a sole enamine functionality, and an additional difficulty that lies in the possibility of hydrogenolysis into the primary amine in the presence of hydrogen and a metal catalyst. This substrate was easily prepared by the condensation of tetralone and benzylamine in boiling toluene using a Dean–Stark apparatus in less than 30 min and without the addition of TsOH.[9a] A strategy based on parallel experimental plans was conveniently used to rapidly determine which type of transition metal (or combination of metal/co-catalyst) was able to perform the enantioselective hydrogenation of benzyl-(3,4-dihydronaphthalen-2-yl)-amine (Scheme 1).



Scheme 1.

We tested a small library of enantiomerically pure *P,P*- and *P,N*-ligands such as diphosphines, phosphine-oxazolines and monodentate phosphorus ligands in association with different metal precursors such as rhodium and iridium complexes, which had revealed efficiency in the enantioselective hydrogenation of enamines,[11] and ruthenium precursors as well (Figs. 1 and 2).

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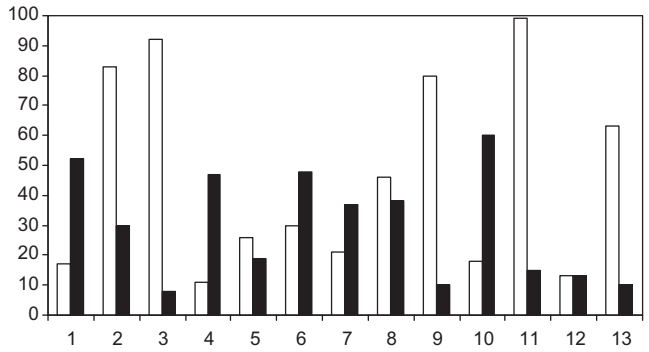


Figure 1. Enantioselective hydrogenation of benzyl-(3,4-dihydronaphthalen-2-yl)-amine with iridium complexes.[12] Conversion was measured by GC. Enantiomeric excess was measured by chiral HPLC. Yields are white bars; Enantiomeric excesses are black bars. Hydrogenation was carried out at 50 °C, 30 bar of H_2 for 24 h in THF for entries 1–6, 8–10, 12; in toluene for entry 7; in MeOH for entries 11 and 13.

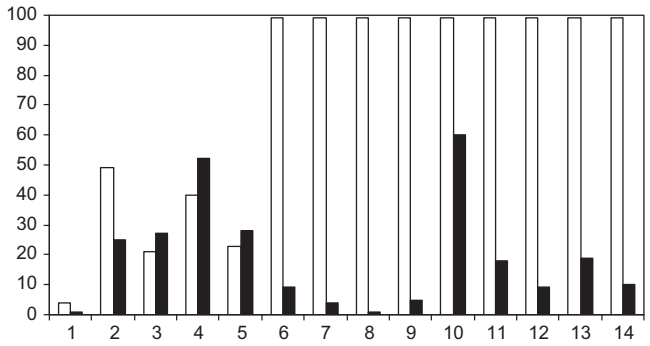


Figure 2. Enantioselective hydrogenation of benzyl-(3,4-dihydronaphthalen-2-yl)-amine with ruthenium complexes.[13] Conversion was measured by GC. Enantiomeric excess was measured by chiral HPLC. Yields are white bars. Enantiomeric excess are black bars. Hydrogenation was carried out at 50 °C, 30 bar of H_2 for 24 h in CH_2Cl_2 for entries 1–5; in MeOH for entries 6–9, 14; in EtOH for entries 10–13.

Under these experimental conditions, rhodium complexes with *P*-monodentate BINOL-based phosphites, (*R,R*)-Me-Duphos and (*R,R*)-Deguphos showed poor enantioselectivity and conversion, and were not considered for further investigation. With iridium catalysts, the best conversions were usually associated with low enantioselectivities (Fig. 1—entries 2, 3, 9, 11 and 13). With ruthenium precursors, with the exception of the $RuCp^*$- and $RuCl_2$-containing systems, most of the other tested catalytic systems revealed high activity and led to complete conversion into the amine. The addition of HBF_4 to the [Ru(cod)(methallyl)$_2$+diphosphine] system, which is known to generate very efficient catalysts in the hydrogenation of tetrasubstituted C=C double bonds[9c,14] led to high conversion but had a detrimental effect on the enantioselectivity (Fig. 2—entries 7–9). Finally, this screening of ruthenium and iridium complexes led to two promising in situ generated catalytic systems: {[Ir(cod)Cl]$_2$ + 4 P(O)(H)((*S*)-BINOL)}, and {Ru(cod)$(O_2CCF_3)_2$ + (*S*)-MeO-Biphep}. These two catalytic systems allowed us to perform the enantioselective hydrogenation of benzyl-(3,4-dihydronaphthalen-2-yl)-amine with up to 60% enantiomeric excess ((+) 60% ee—Fig. 1, entry 10; (−) 60% ee—Fig. 2, entry 10).

The absolute configuration of (2*S*)-(−)-benzyl-(1,2,3,4-tetrahydronaphthalen-2-yl)-amine was determined by measurement of the specific rotation of the corresponding (2*S*)-(−)-(1,2,3,4-tetrahydronaphthalen-2-yl)-amine,[15] which was obtained by catalytic debenzylation of benzyl-(1,2,3,4-tetrahydronaphthalen-2-yl)-amine in the presence of 10 mol % Pd/C in EtOH under 5 bar of hydrogen.[16]

An optimization of the reaction conditions was attempted by fine tuning of pressure, solvent and reaction temperature. In order to improve the enantioselectivity multi-component catalytic systems were used. Thus, the influence of different additives such as AgOTf, I_2,[4b,c,17] PPh_3[18] and HBF_4[9c,14] was studied. Unfortunately, no positive effect on the enantioselectivity was observed.

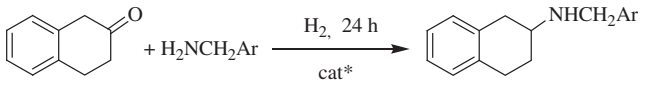
In order to study the solvent effect on the conversion and enantioselectivity, reaction with superior complexes were studied in more detail. From the variety of the solvents THF was chosen for the reason of high enantioselectivity for the iridium complexes.

The results obtained with ruthenium catalysts in different solvents are presented in Table 1, which clearly shows that the best conversions and highest ee-values were obtained with alcohols as solvents.

Table 1
Enantioselective hydrogenation of benzyl-(3,4-dihydronaphthalen-2-yl)-amine with {Ru(cod)$(O_2CCF_3)_2$ + (*S*)-MeO-Biphep} catalytic system in various solvents

Entry	Solvent	Conv. (%)[a]	ee (%)[b]
1	MeOH	99	45 (*S*)
2	EtOH	99	60 (*S*)
3	*i*-PrOH	99	15 (*S*)
4	CF_3CH_2OH	99	2 (*S*)
5	THF	8	n.d.
6	Ethyl acetate	64	3 (*S*)
7	Toluene	14	14 (*S*)
8	CH_2Cl_2	99	7 (*S*)

[a] Conversion was measured by GC.
[b] Enantiomeric excess was measured by chiral HPLC.



Scheme 2.

Our initial concept was that the catalyst should be able to promote the condensation of an amine with a ketone, and catalyze the enantioselective hydrogenation of the formed prochiral unsaturated intermediate to give an enantiomerically pure amine. But kinetic investigations showed that the condensation of tetralone and benzylamine in CD_2Cl_2 took place very rapidly and addition of {[Ir(cod)Cl]$_2$ + 4 P(O)(H)(*S*-BINOL)} as a Lewis acid did not bring any rate increase of this step. During the investigation of intermediates in the hydrogenation reaction, it was discovered that the system studied contained not only the expected enamine. According to deutero-exchange in ^1H and ^{13}C NMR data in MeOD a complex mixture of *N,O*-acetals and half-aminals in large excess was found. It is reasonable to assume that the production of amines in alcohol is associated with the formation of such adducts during the condensation of 2-tetralone and benzylamine.[3b,19]

Knowing this, we started testing the catalytic efficiency of our best systems in a one-pot reductive amination reaction (Scheme 2).

In our initial experiments carried out in dichloromethane with $RuCl_2$((*S*)-MeO-Biphep)$(CH_3CN)_2$[20] as a catalyst, the formation of alcohol as a by-product was observed. Further investigation of the co-catalysts effect on the reaction allowed us to manage this problem. Indeed, the presence of ammonium chloride suppressed the formation of alcohol and led the formation of the desired amine in 52% conversion with 42% ee (Table 2, entry 3). By using the in situ prepared catalytic system {Ru(cod)$(O_2CCF_3)_2$ + (*S*)-MeO-Biphep} in EtOH, at 50 °C under 30 bar of H_2 pressure, it was possible to improve the enantiomeric excess up to 47% and the desired amine was obtained in 83% isolated yield (Table 2).

In order to improve the efficacy of the in situ prepared catalytic system, the isolated Ru$(O_2CCF_3)_2$((*S*)-MeO-Biphep) complex was synthesized. However the same catalytic outcome was observed when this precursor was used under similar conditions.

Table 2
One-pot catalytic asymmetric reductive amination of 2-tetralone with benzylamine

Entry	Catalyst	Solvent	Additive	Yield[a] (%)	ee[b](%)
1	$[Ir(cod)Cl]_2$ + 4 P(O)(H)(*S*-BINOL)	THF	—	12	24 (*R*)
2	$RuCl_2$((*S*)-MeO-Biphep)$(CH_3CN)_2$	CH_2Cl_2	—	33	38 (*S*)
3	$RuCl_2$((*S*)-MeO-Biphep)$(CH_3CN)_2$	CH_2Cl_2	NH_4Cl	52	42 (*S*)
4	$Ru(cod)(O_2CCF_3)_2$ + (*S*)-MeO-Biphep	EtOH	—	83	47 (*S*)

[a] Isolated yield.
[b] Enantiomeric excess was measured by chiral HPLC.

Next, the synthetically more attractive functionalized amines were investigated. The results are presented in Table 3. The typical reaction conditions were used for direct catalytic asymmetric reductive amination. The mixture of 2-tetralone and amine in ethanol was stirred at room temperature for 30 min and then treated with prepared in situ {$Ru(cod)(O_2CCF_3)_2$ + (*S*)-MeO-Biphep} catalytic complex (2 mol %). Then the autoclave was charged with this mixture and pressurized by hydrogen (30 bar H_2; 50 °C; 24 h). It was seen that with electron poor and with electron rich amine analogues, the results were quite similar to those obtained with the parent benzylamine. However, increasing the steric demand with 2,4,6-trimethybenzylamine led to a sharp decrease in enantioselectivity (Table 3, entry 5).

Table 3
One-pot catalytic asymmetric reductive amination of 2-tetralone with various benzylic amines

Entry	$ArCH_2NH_2$	Yield[a] (%)	ee[b] (%)
1	4-$CF_3PhCH_2NH_2$	98	40 (−)
2	4-$MeOPhCH_2NH_2$	72	43 (−)
3	4-$MePhCH_2NH_2$	92	29 (−)
4	2,4-di$MePhCH_2NH_2$	96	45 (−)
5	2,4,6-tri$MePhCH_2NH_2$	99	6 (−)

[a] Isolated yield.
[b] Enantiomeric excess was measured by chiral HPLC.

3. Conclusion

In conclusion, we have demonstrated that the one-pot catalytic asymmetric reductive amination of 2-tetralone is a potentially attractive method for the synthesis of chiral amines. By parallel screening of a small library of ligands incorporated with three different metals (ruthenium, rhodium and iridium), two catalytic system {$[Ir(cod)Cl]_2$ + 4 P(O)(H)(*S*-BINOL)} and {$Ru(cod)(O_2CCF_3)_2$ + (*S*)-MeO-Biphep} were found to be superior. These systems allowed us to perform the indirect transformation via enantioselective hydrogenation of the intermediate benzyl-(3,4-dihydronaphthalen-2-yl)amine with up to 60% enantiomeric excess. The application of these catalytic systems to the direct catalytic asymmetric reductive amination of 2-tetralone gave the desired amine in good yield and with up to 47% enantiomeric excess.

4. Experimental

4.1. General

All syntheses were performed by using standard Schlenk techniques under argon atmosphere. Solvents were purified by standard procedures. The benzyl-(3,4-dihydronaphthalen-2-yl)-amine was prepared by previously described methods.[9a] All other reagents were used as commercially available. ^1H, ^{13}C and ^{19}F NMR spectra were recorded on a Bruker AC 300 MHz spectrometer. The chemical shifts are referenced to tetramethylsilane (^1H and ^{13}C) as the internal standard or CF_3COOH (^{19}F) as the external standard.

4.2. Typical procedure for the hydrogenation of benzyl-(3,4-dihydronaphthalen-2-yl)-amine

A dry 25-mL Schlenk flask under an atmosphere of argon was charged with 0.02 mmol of the ligand and 0.02 mmol of metal complex. A degassed and distilled solvent was added (6 mL) and the mixture was stirred at room temperature for 30 min. Then 1 mmol of the substrate was added by syringe. The hydrogenation experiments were carried out in a parallel manner using four autoclaves. A dry autoclave under argon atmosphere was charged with the reaction mixture. Vacuum was applied three times and hydrogen was introduced. Hydrogenation was carried out at 50 °C, 30 bar H_2 for 24 h. Following dilution, conversion was determined by gas chromatography (GC). Purification by flash chromatography (silica gel, petroleum ether/EtOAc = 4:1) gave the pure product.

4.3. The typical procedure for the one-pot reductive amination reaction

A dry 25-mL Schlenk flask under an atmosphere of argon was charged with 1 mmol of the 2-tetralone and 1 mmol of benzylamine. A degassed and distilled solvent was added (6 mL) and the mixture was stirred at room temperature for 30 min. Then 0.02 mmol of catalytic complex in 2 mL of the same solvent was added by syringe. The hydrogenation experiments were carried out in a parallel manner using four autoclaves. A dry autoclave under argon atmosphere was charged with the reaction mixture. Vacuum was applied three times and hydrogen was introduced. Hydrogenation was carried out at 50 °C, 30 bar H_2 for 24 h. Following dilution, conversion and distribution of products were determined by GC–MS chromatography. Purification by flash chromatography (silica gel, petroleum ether/EtOAc = 4:1) gave the pure products.

4.3.1. Benzyl-(3,4-dihydro-naphthalen-2-yl)amine

^1H NMR (300 MHz, $CDCl_3$) δ_H 7.45 (m, 5H), 7.16 (m, 2H), 6.96 (d, *J* = 7.6 Hz, 2H), 5.42 (s, 1H), 4.34 (s, 2H), 3.62 (s, 1H), 2.94 (t, *J* = 7.9 Hz, 2H), 2.40 (t, *J* = 7.9, 1H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ_C 146.2, 138.9, 137.5, 131.2, 128.7, 127.9, 127.5, 126.9, 126.7, 123.7, 122.7, 93.3, 47.9, 29.1, 28.6; HRMS (EI) calcd for $C_{17}H_{17}N$, $[M]^+$ 235.13610, found 237.1562; Anal. calcd for $C_{17}H_{17}N$: C, 86.77; H, 7.28; N, 5.95. Found: C, 87.22; H, 7.02; N, 5.76.

4.3.2. Benzyl-(1,2,3,4-tetrahydronaphthalen-2-yl)amine

^1H NMR (300 MHz, $CDCl_3$) δ_H 7.43 (m, 5H), 7.17 (m, 4H), 3.98 (s, 2H), 3.09–2.93 (m, 5H), 2.16 (m, 1H), 1.76 (m, 1H), 1.58 (s, 1H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ_C 141.1, 136.7, 135.8, 129.8, 129.2, 128.9, 128.6, 127.4, 126.2, 126.1, 53.2, 51.6, 37.2, 30.0, 28.5; HRMS (EI) calcd for $C_{17}H_{19}N$, $[M]^+$ 237.15175, found 237.1540; Anal. calcd for $C_{17}H_{19}N$: C, 86.03; H, 8.07; N, 5.90. Found: C, 85.34; H, 8.06; N, 5.60. Enantiomeric excess was determined by chiral HPLC (Chiralpak AD column 254 mm, 4.6-mm ID, hexane/2-propanol (90:10), 0.6 mL/min, t_{R1} 8.4 min, t_{R2} 9.4 min). $[\alpha]_D^{22} = -21.5$ (*c* 0.067, CH_2Cl_2, for 60% ee material from entry 10, Fig. 2).

4.3.3. (4-Methylbenzyl)-(1,2,3,4-tetrahydronaphthalen-2-yl)amine

^1H NMR (300 MHz, $CDCl_3$) δ_H 7.23 (m, 4H), 7.14 (m, 4H), 3.94 (s, 2H), 3.16 (m, 2H), 2.94 (m, 2H), 2.72 (m, 1H), 2.44 (s, 3H), 2.23 (m, 1H), 1.72 (m, 1H), 1.65 (s, 1H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ_C 138.6,

136.4, 135.9, 130.5, 129.6, 128.8, 128.7, 127.1, 126.1, 126.0, 53.6, 49.1, 36.9, 29.8, 28.1, 19.1; HRMS (ESI) calcd for $C_{18}H_{22}N$, $[M+H]^+$ 252.17522, found 252.1751; Anal. calcd for $C_{18}H_{21}N$: C, 86.01; H, 8.42; N, 5.57. Found: C, 85.40; H, 8.36; N, 5.10. Enantiomeric excess was determined by chiral HPLC (Chiralpak AD column 254 mm, 4.6-mm ID, hexane/2-propanol (90:10), 0.6 mL/min, t_{R1} 7.9 min, t_{R2} 8.6 min). $[\alpha]_D^{22} = -7.6$ (*c* 0.0112, $CHCl_3$, for 29% ee material from entry 3, Table 3).

4.3.4. (2,4-Dimethylbenzyl)-(1,2,3,4-tetrahydronaphthalen-2-yl)amine

^1H NMR (300 MHz, $CDCl_3$) δ_H 7.26 (d, J = 6.0 Hz, 1H), 7.15 (m, 5H), 7.05 (m, 1H), 7.03 (d, J = 6.0 Hz, 1H), 3.91 (s, 2H), 3.14 (m, 2H), 2.97 (m, 2H), 2.75 (m, 1H), 2.41 (s, 3H), 2.36 (s, 3H), 2.17 (m, 1H), 1.71 (m, 1H), 1.69 (s, 1H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ_C 136.6, 136.5, 136.3, 135.9, 135.7, 131.3, 129.6, 128.8, 128.7, 126.0, 125.9, 125.8, 53.5 48.9, 36.9, 29.8, 28.2, 21.2, 19.1; HRMS (ESI) calcd for $C_{19}H_{24}N$, $[M+H]^+$ 266.19087, found 266.1915; Anal. calcd for $C_{19}H_{23}N$: C, 85.99; H, 8.74; N, 5.28. Found: C, 86.35; H, 8.75; N, 4.89. Enantiomeric excess was determined by chiral HPLC (Chiralpak AD column 254 mm, 4.6-mm ID, hexane/2-propanol (95:5), 0.6 mL/min, t_{R1} 8.5 min, t_{R2} 9.0 min). $[\alpha]_D^{22} = -18.5$ (*c* 0.0183, $CHCl_3$, for 45% ee material from entry 4, Table 3).

4.3.5. (4-Trifluoromethylbenzyl)-(1,2,3,4-tetrahydronaphthalen-2-yl)amine

^1H NMR (300 MHz, $CDCl_3$) δ_H 7.73 (dd, J = 37.2 Hz, J = 12.0 Hz, 4H), 7.26 (m, 4H), 4.08 (s, 2H), 3.15 (m, 2H), 3.01 (m, 2H), 2.87 (m, 1H), 2.18 (m, 2H), 1.83 (s, 1H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ_C 145.3, 136.7, 136.3, 135.6, 135.1, 129.9, 129.2, 128.9, 126.4, 126.3, 125.6 (q, J = 7.5 Hz), 53.4, 51.0, 37.2, 29.9, 28.4; ^{19}F NMR (282 MHz, $CDCl_3$) δ_F −62.7 (s); HRMS (ESI) calcd for $C_{18}H_{19}NF_3$, $[M+H]^+$ 306.14696, found 306.1467; Anal. calcd for $C_{18}H_{18}NF_3$: C, 70.80; H, 5.94; N, 4.59. Found: C, 71.13; H, 6.04; N, 4.24. Enantiomeric excess was determined by chiral HPLC (Chiralpak AD column 254 mm, 4.6-mm ID, hexane/2-propanol (95:5), 0.6 mL/min, t_{R1} 9.1 min, t_{R2} 10.3 min). $[\alpha]_D^{22} = -22.3$ (*c* 0.0153, $CHCl_3$, for 40% ee material from entry 1, Table 3).

4.3.6. (4-Methoxybenzyl)-(1,2,3,4-tetrahydronaphthalen-2-yl)-amine

^1H NMR (300 MHz, $CDCl_3$) δ_H 7.37 (d, J = 6.0 Hz, 2H), 7.17 (m, 4H), 6.95 (d, J = 6.0 Hz, 2H), 3.92 (s, 2H), 3.86 (s, 3H), 3.14 (m, 2H), 3.07 (m, 2H), 2.74 (m, 1H), 2.13 (m, 1H), 1.76 (m, 1H), 1.54 (s, 1H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ_C 158.7, 136.4, 135.4, 132.8, 129.4, 129.3, 128.7, 125.8, 125.7, 113.9, 55.3, 52.8, 50.6, 36.8, 29.6, 28.1; HRMS (ESI) calcd for $C_{18}H_{22}NO$, $[M+H]^+$ 268.17014, found 268.1702; Anal. calcd for $C_{18}H_{21}NO$: C, 80.86; H, 7.92; N, 5.24. Found: C, 80.68; H, 7.60; N, 5.28. Enantiomeric excess was determined by chiral HPLC (Chiralcel OJ column 254 mm, 4.6-mm ID, hexane/2-propanol (95:5), 0.6 mL/min, t_{R1} 27.8 min, t_{R2} 29.6 min). $[\alpha]_D^{22} = -31.05$ (*c* 0.0033, $CHCl_3$, for 43% ee material from entry 2, Table 3).

4.3.7. (2,4,6-Trimethylbenzyl)-(1,2,3,4-tetrahydro-naphthalen-2-yl)amine

^1H NMR (300 MHz, $CDCl_3$) δ_H 7.44 (m, 4H), 7.21 (s, 2H), 4.18 (s, 2H), 3.40 (m, 2H), 3.26 (m, 2H), 3.01 (m, 1H), 2.75 (s, 6H), 2.63 (s, 3H), 2.44 (m, 1H), 2.02 (m, 1H), 1.28 (s, 1H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ_C 137.1, 136.6, 136.5, 135.8, 134.4, 129.7, 129.4, 129.0, 126.1, 126.0, 54.6, 45.6, 37.2, 30.1, 28.4, 21.3, 19.8; HRMS (ESI) calcd for $C_{20}H_{26}N$, $[M+H]^+$ 280.20653, found 280.2063; Anal. calcd for $C_{20}H_{25}N$: C, 85.97; H, 9.02; N, 5.01. Found: C, 86.15; H, 8.72; N, 5.13. Enantiomeric excess was determined by chiral HPLC (Chiralcel OJ column 254 mm, 4.6-mm ID, hexane/2-propanol (95:5), 0.6 mL/min, t_{R1} 11.8 min, t_{R2} 12.5 min). $[\alpha]_D^{22} = -2.4$ (*c* 0.0075, $CHCl_3$, for 6% ee material from entry 5, Table 3).

4.4. Typical procedure for the debenzylation of (−)-benzyl-(1,2,3,4-tetrahydronaphthalen-2-yl)amine

(−)-Benzyl-(1,2,3,4-tetrahydronaphthalen-2-yl)amine (237 mg, 1 mmol) (60% ee) was dissolved in absolute EtOH (10 mL), 10% Pd/C catalyst (100 mg) was added, and the amine was debenzylated in a steel autoclave for 2 h at 45 °C under a H_2 pressure of 5 bar. After filtering off the catalyst, the volatiles were removed under reduced pressure to give a brown oil. The crude oil was purified by flash chromatography (silica gel, eluting with $CHCl_3$/MeOH/iPrNH$_2$ = 9:0.5:0.5) to yield 128 mg of (2*S*)-(1,2,3,4-tetrahydronaphthalen-2-yl)amine (0.87 mmol, 87% yield).

4.4.1. (2*S*)-(1,2,3,4-Tetrahydronaphthalen-2-yl)-amine[15]

$[\alpha]_D^{22} = -51.2$ (*c* 0.018, $CHCl_3$, for 60% ee). ^1H NMR (300 MHz, $CDCl_3$) δ_H 7.20–7.02 (m, 4H), 3.22 (m, 1H), 3.09 (dd, J = 16.2, 4.2 Hz, 1H), 2.91 (m, 2H), 2.62 (dd, J = 16.2, 9.4 Hz, 1H); 2.02 (m, 1H); 1.64 (m, 1H); 1.40 (s, 2H); ^{13}C NMR (75.5 MHz, $CDCl_3$) δ_C 135.9, 135.4, 129.3, 128.7, 125.8, 125.7, 47.4, 39.6, 33.0, 28.1; HRMS (EI) calcd for $C_{10}H_{13}N$, $[M]^+$ 147.1048, found 147.1052; Anal. calcd for $C_{10}H_{13}N$: C, 81.59; H, 8.90; N, 9.51. Found: C, 81.65; H, 8.88; N, 9.47.

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12. Iridium complexes: **1** $[Ir(cod)Cl]_2$ + 4 (*S*)-(3,5-dioxa-4-phospha-cyclohepta[2,1-*a*3,4-*a*′]dinaphthalen-4-yl)bis[(1*S*)-1-phenylethyl]amine; **2** iridium, [(11b*S*)-*N*,*N*-bis[(1*S*)-1-phenylethyl]dinaphtho[2,1-*d*:1′,2′-*f*][1,3,2]dioxaphosphepin-4-amine-κP4][(1,2,5,6-η)-1,5-cyclooctadiene][(2*R*)-2-[[(11b*S*)-dinaphtho[2,1-d:1′,2′-*f*][1,3,2]dioxaphosphepin-4-yl-κP4][(1*S*)-1-phenylethyl]amino]-2-phen-

ylethyl-κC]; **3** Iridium, chloro[(1,2,5,6-η)-1,5-cyclooctadiene][(11b*S*)-*N*,*N*-dimethyldinaphtho[2,1-*d*:1′,2′-*f*][1,3,2]dioxaphosphepin-4-amine-κP4]; **4** $[Ir(cod)Cl]_2$ + 4 dinaphtho[2,1-*d*:1′,2′-*f*][1,3,2]dioxaphosphepin-4-amine, 8,9,10,11,12,13,14,15-octahydro-*N*,*N*-dimethyl-, (11b*S*); **5** $[Ir(cod)Cl]_2$ + 4 dinaphtho[2,1-*d*:1′,2′-*f*][1,3,2]dioxaphosphepin-4-amine, *N*,*N*,2,6-tetramethyl-, (11b*S*); **6** $[Ir(cod)Cl]_2$ + 2 phosphinous acid, *P*,*P*-diphenyl-, (1*S*,2*S*,5*R*)-5-methyl-2-(1-methylethyl)-1-(2-pyridinyl)cyclohexyl ester; **7** [Ir(cod)((*S*)-*i*Pr-PHOX)]Barf; **8** $[Ir(cod)Cl]_2$ + 4 dinaphtho[2,1-*d*:1′,2′-*f*][1,3,2]dioxaphosphepin, 4-phenyl-, (*S*); **9** $[Ir(cod)Cl]_2$ + 2 (*S*)-BINAP; **10** $[Ir(cod)Cl]_2$ + 4 P(O)(H)(*S*-BINOL); **11** $[Ir(cod)Cl]_2$ + 2 (*S*)-MeO-Biphep; **12** $[Ir(cod)Cl]_2$ + 2 (*S*,*S*)-Me-Duphos; (**13**) $[Ir(cod)Cl]_2$ + 2 (*R*)-QUINAP.

13. Ruthenium complexes: **1** $[Cp^*Ru((S,S)\text{-Et-Duphos})Cl]PF_6$; **2** $[Cp^*RuL^1(CH_3CN)_2]PF_6$, were L^1 = (*S*)-(3,5-dioxa-4-phospha-cyclohepta[2,1-*a*3,4-*a*′]dinaphthalen-4-yl)bis[(1*S*)-1-phenylethyl]amine; **3** $[RuCl_2((S)\text{-MeO-Biphep})((1S,2S)\text{-1,2-diamino-1,2-diphenylethane})]$; **4** $RuCl_2((S)\text{-MeO-Biphep})(CH_3CN)_2$; **5** Ru((*S*)-MeO-Biphep)(*p*-cymene); **6** $Ru(cod)(methallyl)_2$ + (*S*,*S*)-Me-Duphos; (**7**) $Ru(cod)(methallyl)_2$ + (*S*)-BINAP + 2 HBF_4; **8** $Ru(cod)(methallyl)_2$ + (*S*,*S*)-Me-BPE + 2 HBF_4; **9** $Ru(cod)(methallyl)_2$ + (*S*)-MeO-Biphep + 2 HBF_4; **10** $Ru(cod)(O_2CCF_3)_2$ + (*S*)-MeO-Biphep; **11** $Ru(cod)(O_2CCF_3)_2$ + (*S*)-Me-Biphemp; **12** $Ru(cod)(O_2CCF_3)_2$ + (*S*)-BINAP; **13** $Ru(cod)(O_2CCF_3)_2$ + (*S*,*S*)-Norphos; **14** chloro{[(1*S*,2*S*)-(+)-2-amino-1,2-diphenylethyl](4-toluenesulfonyl)amido}(*p*-cymene)ruthenium(II).
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