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Palladium catalyzed asymmetric allylic alkylation using chelating *N*-heterocyclic carbene–amino ligands

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Abstract—Several silver(I) complexes with chiral amino-*N*-heterocyclic carbene (NHC) ligands, which are not diastereomerically pure, were prepared and used to generate in situ chelating NHC–amino palladium(II) complexes. The potential of these palladium(II) complexes in asymmetric catalysis was evaluated in the allylic alkylation reaction. The influence of the structure and of the diastereomeric purity of the ligands on enantioselectivity, as well as the role of the silver salts, were studied. Enantiomeric excesses of up to 80% were obtained with the best ligand.

1. Introduction

N-Heterocyclic carbenes (NHC) have emerged as an important family of ligands with strong σ-donor electronic properties and have been used in a wide range of catalytic reactions.[1–4] Lappert et al. reported for the first time in 1983, the synthesis of chiral Rh(I) and Co(I) imidazolinylidene complexes.[5] Over the last ten years, many efforts have been made to synthesize novel chiral NHC ligands and their corresponding metal complexes. Some of these complexes were tested in asymmetric catalysis and excellent levels of enantioselectivity could be reached (up to >99% ee).[6–8] Among these chiral ligands, some heteroditopic NHC–N ligands were reported. Several research groups described the synthesis and the use of NHC–oxazoline ligands[9–16] with good results particularly in the iridium catalyzed hydrogenation of alkenes[10,11,14] and the rhodium catalyzed hydrosilylation of ketones.[13] Palladium(II) complexes bearing chelating NHC–imino ligands, reported by Douthwaite et al. in 2003,[17] gave the best enantioselectivities in palladium catalyzed reactions (ee up to 92%). Comparatively, the formation and the use of metal complexes with chiral NHC–amino ligands have attracted less attention. To our knowledge, only one example of an enantiopure NHC–amino palladium complex was described in 2004.[18] A chiral racemic NHC–amino silver(I) complex was also reported.[19] These complexes have not been tested in asymmetric catalysis.

In contrast to other palladium catalyzed reactions, the allylic alkylation reaction was little studied with NHC ligands. The first example was reported by Mori and Sato in 2003,[20,21] who described a nonasymmetric version (although a chiral ligand was tested). Enantioselective versions were reported by Douthwaite et al. in 2003 and 2005 (up to 92% ee)[17,22] and very recently by Wang et al. who obtained up to 87% ee using NHC ligands derived from podophyllotoxin.[23]

We previously reported the preparation and the structure of several chiral NHC–palladium complexes[24–27] including two complexes bearing chelating NHC–amino ligands[27] (Fig. 1), which were obtained by reaction of the corresponding silver complexes with 1 equiv of $PdCl_2(CH_3CN)_2$. The chelating properties of these NHC–amino ligands were demonstrated by X-ray analysis of one of the palladium complexes. Only two NHC–amino silver complexes were previously described, but a general method was developed for the synthesis of various precursor amino–imidazolium salts.

Herein we report the preparation of a small library of chiral NHC–amino silver(I) complexes and their use for the in situ generation of palladium complexes, tested in the asymmetric allylic alkylation reaction.

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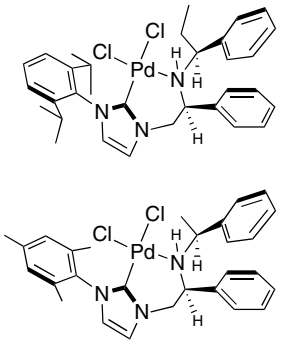


Figure 1.

2. Results and discussion

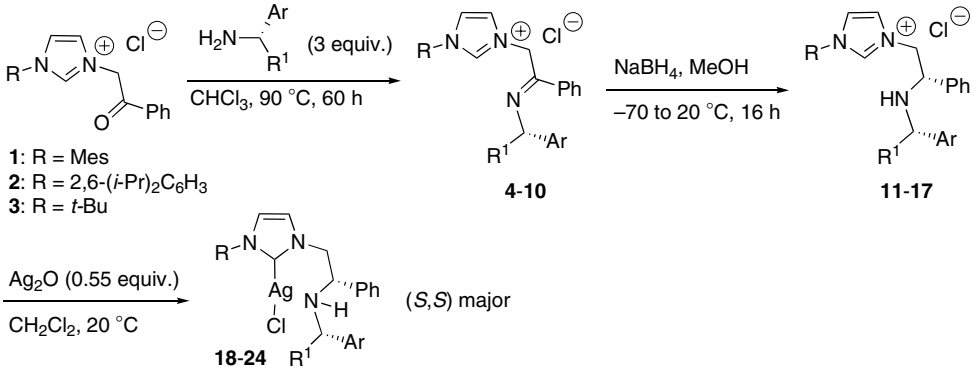
2.1. Synthesis of chiral NHC–amino silver(I) complexes

The synthetic method previously developed[27] was extended to the preparation of several silver(I) complexes (Scheme 1 and Table 1): Various chiral and commercially available secondary amines could be condensed to 1-(2-oxo-ethyl)-imidazolium salts **1**–**3**, bearing a mesityl, a 2,6-diisopropylphenyl or a *t*-butyl group on one of the nitrogen atoms of the azolium, affording imino–imidazolium salts **4**–**10** in 67–92% yields. Reduction of the imino salts with $NaBH_4$ in MeOH gave amino–imidazolium salts **11**–**17** with dr ranging from 80:20 to 90:10 and in 65–99% yields. The (*S*,*S*) configuration of the major diastereomers was previously determined by X-ray analysis.[27] Finally, reaction of amino–imidazolium salts **11**–**17** with 0.55 equiv of Ag_2O[28] led to the expected NHC–amino silver(I) complexes **18**–**24** in 70–94% yield without noticeable change of the diastereomeric ratio.

2.2. Palladium catalyzed asymmetric allylic alkylation with NHC–amino ligands

The efficiency of NHC–amino ligands in asymmetric catalysis must be directly dependent on the aptitude of the nitrogen atom (of the chiral moiety) for effectively complexing the palladium under the conditions of the reaction. Their potential in asymmetric catalysis was, therefore, evaluated on the palladium catalyzed allylic alkylation of (*E*)-1,3-diphenylprop-3-en-yl acetate **25** with dimethyl malonate (Scheme 2).[29] A test reaction was previously performed in THF using diastereomerically pure silver complex **18** and $[Pd(allyl)Cl]_2$. After generation of the NHC–Pd complex, the silver salts were removed by filtration. Allylation product **26** was isolated in 41% yield and 60% ee after 16 h at 20 °C.[27] However, the use of ligands with high diastereomeric purities (>98:2) has been a limitation to test a wide range of ligand structures. In some cases, we showed that the major diastereomer of the amino–imidazolium salt could be separated from the mixture by crystallization, although only amino–imidazolium salts **11** and **15** could be isolated with a dr >98:2 and acceptable yields using this procedure. Consequently, we decided to firstly test the silver complexes **18**–**24** as mixture of diastereomers. We also considered that the filtration of the silver salts after transfer of the NHC ligand onto palladium, which is experimentally constraining, could be avoided to make the procedure easier. Therefore, the reactions were initially carried out in the presence of silver chloride. In preliminary experiments, the following observations were made: (a) the best base for the deprotonation of the malonate was found to be NaH, *t*-BuOK affording slightly higher yields but lower enantioselectivities and the BSA/AcOK system lower yields and enantioselectivities. (b) The more effective palladium precursor complex was $[PdCl(allyl)]_2$. $Pd(OAc)_2$ and $Pd_2(dba)_3$ both gave lower yields and enantioselectivities. (c) No reaction occurred in CH_2Cl_2 at 20 °C contrary to THF and reactions performed in THF at higher temperatures led to a decrease in enantioselectivity. From these observations, two standard procedures were developed to test silver complexes **18**–**24**. The reactions were carried out either in THF at 20 °C or in CH_2Cl_2 at 40 °C. The results are presented in Table 2. In a typical procedure, $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ (3 mol %) and the silver complex (8.5 mol %) were stirred in the indicated solvent for 1 h at 20 °C. A solution of (*E*)-1,3-diphenylprop-3-en-yl acetate and a solution of dimethylmalonate/NaH were then added and the suspension was stirred for 48 h (THF) or 16 h (CH_2Cl_2) at the indicated temperature.

As shown in Table 2, the stereochemistry and enantioselectivity strongly depend on the R substituent of the NHC (see Scheme 1 and Table 1 for structures). The (*R*)-enantiomer is favoured when an aromatic substituent is present on

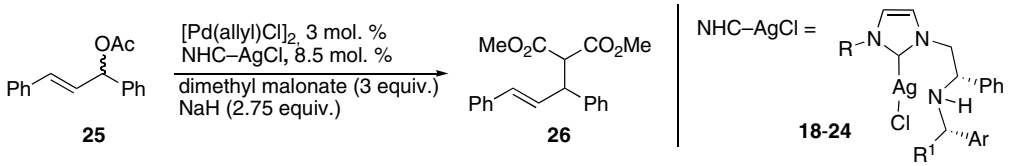


Scheme 1.

Table 1. Preparation of NHC–amino silver(I) complexes **18**–**24**

R	Ar	R^1	Imine (yield %)	Amine (yield %) (dr)[a]	Ag(I) Complex (yield %)
Mes	Ph	Me	**4** (87)	**11** (91) (85:15)	**18** (80)
Mes	Ph	Et	**5** (81)	**12** (80) (87:13)	**19** (70)
Mes	1-Naphth	Me	**6** (90)	**13** (80) (90:10)	**20** (75)
2,6-(*i*-Pr)$_2$C$_6$H$_3$	Ph	Me	**7** (92)	**14** (87) (84:16)	**21** (56)
2,6-(*i*-Pr)$_2$C$_6$H$_3$	Ph	Et	**8** (78)	**15** (99) (85:15)	**22** (80)
2,6-(*i*-Pr)$_2$C$_6$H$_3$	4-MeO–C$_6$H$_4$	Me	**9** (67)	**16** (88) (80:20)	**23** (86)
t-Bu	Ph	Me	**10** (88)	**17** (65) (85:15)	**24** (94)

[a] Ratio determined by ^{1}H NMR (400 MHz).



Scheme 2.

Table 2. Asymmetric allylic alkylation with NHC–amino ligands

Entry	Ag(I) Complex	Solvent	*T* (°C)	*t* (h)	Conversion[a] (%)	Yield[b] (%)	ee[c] (%)
1	**18** (dr 85:15)	THF	20	48	50	39	50 (*R*)
2	**19** (dr 87:13)	THF	20	48	50	38	37 (*R*)
3	**20** (dr 90:10)	THF	20	48	58	27	30 (*R*)
4	**21** (dr 84:16)	THF	20	48	48	43	80 (*R*)
5	**21** (dr 84:16)	CH_2Cl_2	40	16	62	52	78 (*R*)
6	**22** (dr 85:15)	THF	20	48	33	15	76 (*R*)
7	**22** (dr 85:15)	CH_2Cl_2	40	16	68	52	80 (*R*)
8	**23** (dr 80:20)	THF	20	48	27	26	69 (*R*)
9	**23** (dr 80:20)	CH_2Cl_2	40	16	96	77	74 (*R*)
10	**24** (dr 85:15)	THF	20	48	8	8	36 (*S*)
11	**24** (dr 85:15)	CH_2Cl_2	40	16	27	25	50 (*S*)

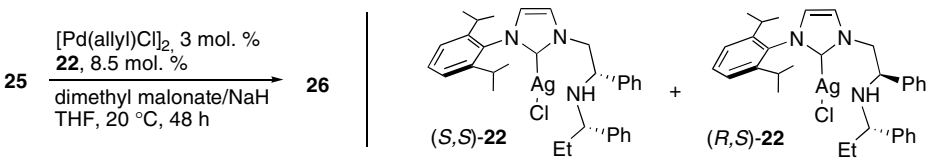
[a] Conversion determined by ^{1}H NMR of the crude (400 MHz) and based on recovered starting material.
[b] Yield after purification by silica gel chromatography.
[c] Enantiomeric excess of **26** determined by ^{1}H NMR with a chiral shift reagent Eu(hfc)$_3$ or HPLC analysis.

the nitrogen (Table 2, entries 1–9) when the (*S*)-enantiomer is major in the case of a *t*-butyl group (entries 10 and 11). The best enantioselectivities (69–80% ee) were obtained with a bulky 2,6-diisopropylphenyl substituent (entries 4–9, silver complexes **21**–**23**). Comparatively, structural variations in the chiral amine moiety have less effect on enantioselectivity. For R = 2,6-diisopropylphenyl (substituent on the NHC), lower enantioselectivities were obtained with the silver complex **23** having a 1-(*p*-methoxyphenyl)ethylamino group on the side chain (entries 8 and 9, 69–74% ee). Silver complexes **21** and **22** having 1-(phenyl)ethylamino or 1-(phenyl)propylamino groups led to the best enantiomeric excesses (entries 4–7, 76–80% ee). Reactions carried out in dichloromethane gave better yields and generally comparable or higher enantioselectivities than in THF.

It is noteworthy that low reaction rates were observed with these NHC ligands and the best yield was only 77% (entry 9). Douthwaite et al. already mentioned that the activity of similar NHC–imino palladium complexes was quite low and that comparatively NHC–P ligands exhibited better activities.[22] In the reaction, the strong σ-donating effect of the NHC[30] may favor the oxidative addition step but may also induce the formation of little electrophilic Pd(II) cationic complexes.

2.3. Influence of the diastereomeric purity of the silver complexes on enantioselectivity

As mentioned above, silver complexes **18**–**24** were obtained and tested as a mixture of diastereomers. It was, therefore, important to estimate the effect of each diastereomer on the stereochemistry and enantioselectivity of the reaction. This effect was evaluated by performing allylic alkylation reactions using silver complex **22** with different proportions of the two diastereomers (Scheme 3). The precursor amino–imidazolium salt **15** was initially obtained as a 85:15 mixture of diastereomers after $NaBH_4$ reduction of imino salt **8** (see Table 1). Salt **15** could be obtained with a diastereomeric ratio of 92:8 after one recrystallization in dichloromethane/acetone/ether and as a single diastereomer (dr >98:2) after a second recrystallization.[27] In the final mother liquor the initially minor (*R*,*S*) diastereoisomer is predominant with a dr of 23:77 ((*S*,*S*):(*R*,*S*)). Four samples



Scheme 3.

of silver complex **22** having different proportions of the two diastereomers could be obtained after treatment of the precursor amino–imidazolium salts by Ag_2O. These samples were tested in the allylic alkylation reaction in THF at 20 °C (Scheme 3). As shown in Table 3, the same stereoselectivity in favor of the (*R*) product was observed in all cases. However, the enantioselectivity is better when the (*S*,*S*) diastereomer is predominant in the mixture (entries 1–3, ee 74–76%) compared to the (*R*,*S*) diastereomer (entry 4, ee 26%). No significant alteration of the enantioselectivity was observed when the diastereomeric ratio changes from >98:2 to 85:15 (entries 1–3). Therefore, we can assume that under our conditions (ratio Pd:NHC = 0.7:1), the use of ligands which are not diastereomerically pure does not affect significantly the enantioselectivity.[31]

Table 3. Influence of the diastereomeric ratio of silver complex **22**

Entry	dr (*S*,*S*):(*R*,*S*)	Conversion[a] (%)	Yield[b] (%)	ee (%)
1	>98:2	34	26	74 (*R*)
2	92:8	55	41	76 (*R*)
3	85:15	33	15	76 (*R*)
4	23:77	19	22	26 (*R*)

[a] Conversion determined by ^{1}H NMR.
[b] Yield after purification by silica gel chromatography.

2.4. Influence of silver chloride

Hou et al. reported in 2005 that the presence of silver salts in the allylic alkylation reaction of acyclic ketones had a beneficial effect in terms of enantioselectivity and yield.[32] We carried out several experiments starting from silver complex **22** in order to better understand the potential role of silver salts in our conditions. The results are presented in Table 4 and Figure 2. In our two standard procedures (THF, 20 °C or CH_2Cl_2, 40 °C), a beneficial effect on enantioselectivity was observed when the silver salts (AgCl), generated after transfer of the NHC ligand onto palladium, were not removed from the reaction media (entries 1–2 and 9–10). Filtration of AgCl at this stage led to a decrease of the ee from 76% to 68% in THF and from 80% to 70% in CH_2Cl_2. To further investigate the influence of silver chloride, an experiment with additional 10 mol % of AgCl was carried out in THF at 20 °C. This addition dramatically reduced the enantioselectivity from 76% to 58% ee (entry 3). Surprisingly, the effect of silver chloride when the reaction was performed in THF at 40 °C (entries 6–8) was found to be inverse to the one observed at 20 °C (see Fig. 2). In this case, the best ee (75%, entry 6) was obtained when the initially formed silver salts were not removed and when additional AgCl (10 mol %) was present in the reaction media. From these results, it is very difficult to rationalize the exact role of AgCl, particularly in THF where its influence seems to be temperature dependent. The addition of $AgBF_4$ (entry 4) or $BnEt_3NCl$ (entry 5) did not modify either the enantioselectivity or the conversion. Consequently, it seems that the effect of AgCl would come from silver cations instead of chloride anions.[33] Silver

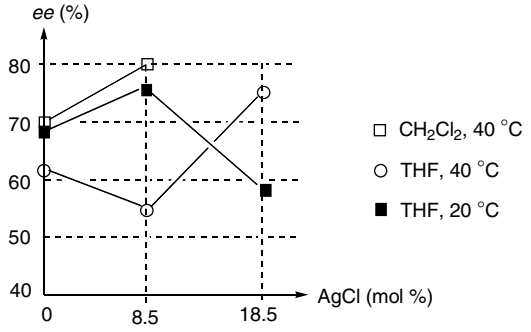


Figure 2.

Table 4. Influence of silver salts in the reaction media

Entry	Filtration of the silver salts	Additive (mol %)	Solvent	*T* (°C)	*t* (h)	Conversion[a] (%)	Yield[b] (%)	ee (%)
1	Yes	None	THF	20	48	22	19	68 (*R*)
2	No	None	THF	20	48	33	15	**76** (*R*)
3	No	AgCl (10)	THF	20	48	21	19	58 (*R*)
4	No	$AgBF_4$ (10)	THF	20	48	18	18	74 (*R*)
5	No	$BnEt_3NCl$ (10)	THF	20	48	27	18	**77** (*R*)
6	Yes	None	THF	40	16	37	36	62 (*R*)
7	No	None	THF	40	16	47	46	54 (*R*)
8	No	AgCl (10)	THF	40	16	54	37	**75** (*R*)
9	Yes	None	CH_2Cl_2	40	16	>98	75	70 (*R*)
10	No	None	CH_2Cl_2	40	16	68	52	**80** (*R*)

NHC–AgCl **22** (8.5 mol %, dr 85:15).
[a] Conversion determined by ^{1}H NMR and based on the recovered starting material.
[b] Yield after purification by silica gel chromatography.

enolates generated from the sodium salt of β-diketones and silver nitrate have been described in 2002.[34] It is likely that such species could be formed in our conditions in the presence of silver chloride.

3. Conclusion

We have shown that the synthetic method that was previously developed could be extended to the preparation of a small library of NHC–amino silver(I) complexes. These latter were used for the in situ generation of palladium complexes that gave up to 80% ee in the asymmetric allylic alkylation reaction. Low reaction rates were observed, probably because of the weak π-acidity of the NHC that disfavours the nucleophile addition step. However, the enantioselectivities obtained confirmed the chelating properties of this family of NHC–amino ligands and their potential application in asymmetric catalysis. Ligands which are not diastereomerically pure could be used without change in the enantioselectivity.

4. Experimental

All experiments were performed under argon using standard Schlenk techniques unless stated otherwise. Solvents were dried over the appropriate drying agent and distilled under dinitrogen. Sodium benzophenone ketyl (THF, Et_2O), CaH_2 (CH_2Cl_2). MeOH and $CHCl_3$ of analytical grade type were used without special drying or distillation. Reagents were purchased from Acros or Aldrich and used as received unless otherwise stated. The preparation and spectroscopic characteristics of imidazolium salts **4**, **7**, **8**, **10**, **11**, **14**, **15** and **17** and silver complexes **18** and **22** have previously been reported.[27] Elemental analyses were performed by the microanalytical service ICSN (CNRS). NMR spectra were recorded on a Brucker ARX 400 instrument, in $CDCl_3$ or CD_2Cl_2 as the solvent. Optical rotations were measured on a Perkin–Elmer 343.

4.1. General procedure for the preparation of imino–imidazolium salts 4–10

In a screw-cap tube flushed with argon were introduced the 1-(2-oxo-2-phenyl)ethyl imidazolium salt **1**, **2**, or **3** (1 mmol), the chiral amine (3 mmol) and 2 mL of $CHCl_3$. A paper trap filled with molecular sieves 4 Å was placed at the top of the tube before closing. The mixture was stirred under argon at 90 °C (oil bath) for 60 h. After cooling, CH_2Cl_2 (2 mL) and $NaHCO_3$ (300 mg, 3.5 mmol) were added and the mixture was stirred vigorously for 1 h, filtered under dinitrogen and concentrated. Imino–imidazolium salts were precipitated from the crude by several washing of the residue with dry Et_2O. The solids obtained were dried under vacuum.

4.1.1. 3-Mesityl-1-[2-{(*S*)-1-(phenyl)propylimino}-2-phenyl ethyl]imidazolium chloride 5. Yield 81%, white powder. Mp 115 °C. $[\alpha]_D^{20} = -26$ (*c* 1.1, $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.69 (t, 3H, $J = 7$ Hz, CH_2–CH_3), 1.65 (m, 2H, $J = 7$ Hz, CH_2–CH_3), 2.11 (s, 3H), 2.18 (s, 3H), 2.40 (s, 3H), 4.35 (t, 1H, $J = 7$ Hz, N–C*H*–Et), 5.45 (d, 1H, $J = 17.3$ Hz, N–C*H*H–C=N), 6.38 (d, 1H, $J = 17.3$ Hz, N–CH*H*–C=N), 7.09 (s, 2H), 7.12–7.15 (m, 3H), 7.21–7.33 (m, 3H), 7.42–7.55 (m, 5H), 7.60 (s, 1H), 10.60 (s, 1H, N–C*H*=N). ^{13}C NMR (100 MHz, CD_2Cl_2): δ 11.0, 17.7, 21.2, 32.7 (CH_2–CH_3), 56.1 (CH_2–C=N), 67.3 (N–*C*H–Et), 122.3, 124.7, 127.1, 127.9, 128.7, 129.1, 129.9, 130.0, 131.4, 134.6, 134.9, 140.3 (N–*C*H=N), 141.5, 144.7, 163.1 (CH_2C=N). Exact MS (ESI+ in MeOH sens = 1.83 e^6) $m/z = 422.32$ for $C_{29}H_{32}N_3$ $[M-Cl]^+$. IR (ATR diamond) $\nu_{C=N}$ 1664 cm^{-1}.

4.1.2. 3-Mesityl-1-[2-{(*S*)-1-(1-naphthyl)ethylimino}-2-phenyl ethyl]imidazolium chloride 6. Yield 90%, pale orange powder. Mp 138 °C. $[\alpha]_D^{20} = +97$ (*c* 1, $CHCl_3$). ^{1}H NMR (400 MHz, CD_2Cl_2): δ 1.26 (d, 3H, $J = 6.3$ Hz, CH–CH_3), 1.89 (s, 3H), 1.95 (s, 3H), 1.98 (s, 3H), 5.21 (q, 1H, $J = 6.3$ Hz), 5.55 (d, 1H, $J = 17.1$ Hz, N–C*H*H–C=N), 6.06 (d, 1H, $J = 17.1$ Hz, N–CH*H*–C=N), 6.87 (m, 2H), 7.15 (s, 1H), 7.19–7.29 (m, 6H), 7.35 (d, 2H, $J = 7$ Hz), 7.40 (d, 1H, $J = 7$ Hz), 7.57 (d, 1H, $J = 8$ Hz), 7.62 (d, 1H, $J = 8$ Hz), 7.68 (d, 1H, $J = 8$ Hz), 7.93 (s, 1H), 10.33 (s, 1H). ^{13}C NMR (100 MHz, CD_2Cl_2): δ 17.7, 17.8, 21.3, 25.2, 56.3 (CH_2), 57.3 (*C*H–CH_3), 122.6, 123.5, 124.0, 125.3, 125.8, 126.1, 127.5, 127.9, 129.1, 129.2, 130.0, 130.4, 131.5, 134.3, 134.6, 134.9, 140.0 (N–*C*H=N), 141.4, 142.0, 162.9 (CH_2C=N). Exact MS (ESI+ in MeOH sens = 1.83 e^9) $m/z = 458.3$ for $C_{32}H_{32}N_3$ $[M-Cl]^+$. IR (ATR diamond) $\nu_{C=N}$ 1656 cm^{-1}.

4.1.3. 3-(2,6-Diisopropylphenyl)-1-[2-{(*S*)-1-(*p*-methoxyphenyl)ethylimino}-2-phenyl ethyl]imidazolium chloride 9. Yield 67%, beige powder. Mp 108 °C. $[\alpha]_D^{20} = -18$ (*c* 1, $CHCl_3$). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.01 (d, 3H, $J = 6.8$ Hz), 1.02 (d, 3H, $J = 6.8$ Hz), 1.04 (d, 3H, $J = 6.8$ Hz), 1.08 (d, 3H, $J = 6.8$ Hz), 1.15 (d, 3H, $J = 6.3$ Hz), 2.20 (m, 1H, $J = 6.8$ Hz), 2.34 (m, 1H, $J = 6.8$ Hz), 3.66 (s, 3H, O*Me*), 4.46 (q, 1H, $J = 6.3$ Hz), 5.58 (d, 1H, $J = 17.2$ Hz, N–C*H*H–C=N), 6.20 (d, 1H, $J = 17.2$ Hz, N–CH*H*–C=N), 6.71 (d, 2H, $J = 8.3$ Hz), 6.97 (d, 2H, $J = 8.3$ Hz), 7.12–7.20 (m, 3H), 7.28 (m, 3H), 7.40–7.44 (m, 3H), 7.89 (s, 1H), 10.38 (s, 1H). ^{13}C NMR (100 MHz, CD_2Cl_2): δ 23.9, 24.1, 24.7, 28.4, 55.2, 55.8 (CH_2), 59.3, 113.7, 123.1, 124.5, 125.1, 127.2, 127.5, 128.6, 129.3, 130.6, 131.6, 134.5, 137.4, 140.0 (N–*C*H=N), 145.6, 158.3, 162.3 (CH_2C=N). HRMS (in CH_3CN, sens = 2.14 e^8): found 480.2999 $[M-Cl]^+$ ($C_{32}H_{38}N_3O$ requires 480.3015). IR (ATR diamond) $\nu_{C=N}$ 1662 cm^{-1}.

4.2. General procedure for the preparation of amino–imidazolium salts 11–17

The imino–imidazolium salt (0.22 mmol) was dissolved in MeOH (5 mL) under argon. The solution was cooled to −70 °C and $NaBH_4$ (33 mg, 0.88 mmol) was added by portions. The mixture was stirred overnight, during which period it was allowed to gradually warm to 20 °C. A saturated aqueous NH_4Cl solution (5 mL) was added and the mixture was stirred vigorously for 10 min. Solid K_2CO_3 was added and the mixture was stirred for 10 min. The methanol was evaporated and the resulting mixture was extracted with CH_2Cl_2. The organic layer was dried over Na_2SO_4 and

concentrated. The product was washed with Et_2O and dried under vacuum.

4.2.1. 3-Mesityl-1-[(2*S*)-2-{(*S*)-1-(phenyl)propylamino}-2-phenyl ethyl]imidazolium chloride 12. Yield 80%, white solid. Mixture of diastereomers (87:13). Major diastereomer: ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.66 (t, 3H, $J = 7.5$ Hz), 1.50–1.83 (m, 2H, CH_3–CH_2), 1.84 (s, 3H), 1.93 (s, 3H), 2.27 (s, 3H), 3.52 (dd, 1H, $J = 8.3$ and 5.3 Hz, Et-C*H*-NH), 4.21 (t, 1H, $J = 5$ Hz, N–CH_2–C*H*–NH), 4.85 (dd, 1H, $J = 11$ and 5 Hz, N–C*H*H–CH–NH), 5.05 (dd, 1H, $J = 11$ and 5 Hz, N–CH*H*–CH–NH), 6.82 (s, 1H), 6.89 (s, 1H), 6.90 (s, 1H), 6.99 (s, 1H), 9.97 (s, 1H), 7.09–7.25 (m, 10H), 10.32 (s, 1H, N–C*H*=N). ^{13}C NMR (100 MHz, $CDCl_3$): δ 10.2, 17.3, 17.5, 21.0, 29.3 (CH_3–CH_2), 54.3 (N–CH_2–CH), 59.9 (C*H*–Ph), 61.1 (C*H*–Ph), 121.9, 123.8, 126.7, 127.2, 127.4, 127.9, 128.1, 128.7, 129.6, 130.8, 134.2, 134.3, 138.8 (N–C*H*=N), 139.5, 140.9, 143.7. Exact MS (ESI+ in CH_3CN sens = 4.17 e^6) $m/z = 410.2$ for $C_{28}H_{32}N_3$ $[M-Cl]^+$.

4.2.2. 3-Mesityl-1-[(2*S*)-2-{(*S*)-1-(1-naphthyl)ethylamino}-2-phenyl ethyl]imidazolium chloride 13. Yield 80%, yellow solid. Mixture of diastereomers (90:10). Major diastereomer: ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.50 (d, 3H, $J = 6.3$ Hz), 1.87 (s, 3H), 2.05 (s, 3H), 2.35 (s, 3H), 4.51 (dd, 1H, $J = 6.0$ and 5.0 Hz, CH_2–C*H*–NH), 4.57 (q, 1H, $J = 6.3$ Hz), 4.90 (dd, 1H, $J = 13.5$ and 6.0 Hz, C*H*H–CH–NH), 5.30 (dd, 1H, $J = 13.5$ and 5.0 Hz, CH*H*–CH–NH), 6.90 (t, 1H, $J = 1.5$ Hz), 6.96 (s, 1H), 6.99 (s, 1H), 7.09 (t, 1H, $J = 1.5$ Hz), 7.25–7.48 (m, 8H), 7.70 (d, 2H, $J = 8$ Hz), 7.83 (d, 2H, $J = 8$ Hz), 10.51 (s, 1H, N–C*H*=N). ^{13}C NMR (100 MHz, $CDCl_3$): δ 17.3, 17.5, 21.0, 22.3, 49.5, 54.6 (CH_2), 59.7, 121.8, 123.0, 123.2, 123.8, 125.2, 125.6, 125.7, 127.0, 127.5, 128.0, 128.7, 128.8, 129.6, 130.5, 130.7, 133.6, 134.2, 139.2, 140.9, 141.6. Exact MS (ESI+ in CH_3CN sens = 6.29 e^9) $m/e = 460.1$ for $C_{32}H_{34}N_3$ $[M-Cl]^+$.

4.2.3. 3-(2,6-Diisopropylphenyl)-1-[(2*S*)-2-{(*S*)-1-(*p*-methoxyphenyl)ethylamino}-2-phenyl ethyl]imidazolium chloride 16. Yield 88%, pale yellow powder. Mixture of diastereomers (80:20). Major diastereomer: ^{1}H NMR (400 MHz, CD_2Cl_2): δ 1.15–1.18 (m, 9H), 1.24 (d, 3H, $J = 6.8$ Hz), 1.31 (d, 3H, $J = 6.3$ Hz), 2.27 (m, 1H, $J = 6.8$ Hz), 2.36 (m, 1H, $J = 6.8$ Hz), 3.74 (q, 1H, $J = 6.3$ Hz), 3.78 (s, 3H), 4.34 (dd, 1H, $J = 6.5$ and 5 Hz, CH_2–C*H*–Ph), 5.05 (dd, 1H, $J = 13.2$ and 6.5 Hz, N–C*H*H–CHPh), 5.11 (dd, 1H, $J = 13.2$ and 5 Hz, N–CH*H*–CHPh), 6.81 (d, 2H, $J = 8.6$ Hz), 7.04 (t, 1H, $J = 1.5$ Hz), 7.24 (d, 2H, $J = 8.6$ Hz), 7.20–7.45 (m, 8H), 7.59 (t, 1H, $J = 7.8$ Hz), 10.51 (t, 1H, $J = 1.5$ Hz, N–C*H*=N). ^{13}C NMR (100 MHz, $CDCl_3$): δ 22.8, 24.0, 24.1, 24.2, 24.4, 28.4, 53.8, 54.5 (CH_2), 55.2, 59.7, 113.7, 122.9, 123.7, 124.4, 124.5, 127.4, 127.5, 127.9, 128.7, 130.3, 131.2, 137.7, 139.3 (N–C*H*=N), 139.4, 145.3, 145.4, 158.3. HRMS (in CH_3CN, sens = 2.59 e^8): found 482.3157 $[M-Cl]^+$ ($C_{32}H_{40}N_3O$ requires 482.3171).

4.3. General procedure for the preparation of silver(I) complexes 18–24

To a solution of imidazolium salt (1 mmol) in dry CH_2Cl_2 (15 mL) was added Ag_2O (0.55 mmol). The mixture was stirred at 20 °C for 16 h with exclusion of light, filtered through Celite, concentrated under reduced pressure and dried under vaccum.

4.3.1. 3-Mesityl-1-[(2*S*)-2-{(*S*)-1-(phenyl)propylamino}-2-phenyl ethyl]imidazol-2-ylidene silver chloride 19. Yield 70%, grey pearl solid. Mixture of diastereomers (87:13). Major diastereomer: ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.72 (t, 3H, $J = 7.3$ Hz), 1.56 (m, 1H, C*H*H–CH_3), 1.71 (s, 3H), 1.73 (m, 1H, CH*H*–CH_3), 1.80 (s, 3H), 2.22 (s, 3H), 3.66 (dd, 1H, $J = 12$ and 6.5 Hz, C*H*–Et), 4.03 (ddd, 1H, $J = 11.4$, 7 and 5.5 Hz, N–CH_2–C*H*(Ph)NH), 4.40 (dd, 1H, $J = 13.5$ and 7 Hz, CH_2–CH–NH), 4.47 (dd, 1H, $J = 13.5$ and 5.5 Hz, CH_2–CH–NH), 6.78 (s, 1H), 6.90–6.94 (m, 3H), 7.12–7.40 (m, 10H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 10.6, 17.6, 17.7, 21.0, 30.0 (CH_2–CH_3), 57.0 (N–CH_2–CH–NH), 61.1, 62.1, 121.7 (d, J^3(Ag–^{13}C) 7 Hz, C*H*=CH), 122.1 (d, J^3(Ag–^{13}C) 7 Hz, CH=C*H*), 127.1, 127.3, 128.2, 128.6, 129.1, 129.4, 134.5, 134.6, 135.2, 139.4, 140.0, 143.3, 181.5 (dd, J^1(^{109}Ag–^{13}C) 271 Hz and J^1(^{107}Ag–^{13}C) 238 Hz, $C_{carbene}$). Exact MS (ESI+ in MeOH sens = 8.16 e^6) $m/e = 424.3$ for $C_{29}H_{34}N_3$ $[M+H-AgCl]^+$.

4.3.2. 3-Mesityl-1-[(2*S*)-2-{(*S*)-1-(1-naphthyl)ethylamino}-2-phenyl ethyl]imidazol-2-ylidene silver chloride 20. Yield 75%, orange solid. Mixture of diastereomers (90:10). Major diastereomer: ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.53 (d, 3H, $J = 6.5$ Hz), 1.80 (s, 3H), 1.92 (s, 3H), 2.32 (s, 3H), 4.26 (t, 1H, $J = 6.3$ Hz, CH_2–C*H*–NH), 4.43 (dd, 1H, $J = 13.5$ and 6.3 Hz, C*H*H–CH–NH), 4.49 (dd, 1H, $J = 13$ and 6.3 Hz, CH*H*–CH–NH), 4.69 (q, 1H, $J = 6.5$ Hz, CH_3–C*H*–Naphth), 6.80 (s, 1H), 6.91 (s, 1H), 6.93 (s, 1H), 6.97 (s, 1H), 7.24–7.54 (m, 8H), 7.56 (d, 1H, $J = 7.0$ Hz), 7.78 (d, 1H, $J = 8.5$ Hz), 7.88 (d, 1H, $J = 8.5$ Hz), 7.98 (d, 1H, $J = 8.5$ Hz). ^{13}C NMR (100 MHz, $CDCl_3$): δ 17.6, 17.7, 21.0, 22.4, 50.4, 57.5 (CH_2–CH–NH), 61.3, 121.9, 122.1, 122.9, 123.0, 125.5, 125.6, 126.0, 127.2, 127.6, 128.3, 129.0, 129.2, 129.3, 130.9, 133.9, 134.5, 134.6, 135.3, 139.4, 139.6, 140.8, 181.4 (dd, J^1(^{109}Ag–^{13}C) 274 Hz and J^1(^{107}Ag–^{13}C) 236 Hz, $C_{carbene}$). Exact MS (ESI+ in CH_3CN sens = 4.19 e^9) $m/e = 460.2$ for $C_{32}H_{33}N_3$ $[M+H-AgCl]^+$.

4.3.3. 3-(2,6-Diisopropylphenyl)-1-[(2*S*)-2-{(*S*)-1-(phenyl)-ethylamino}-2-phenyl ethyl]imidazol-2-ylidene silver chloride 21. Yield 56%, beige powder. Mixture of diastereomers (86:14). Major diastereomer: ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.04 (d, 3H, $J = 7$ Hz), 1.08 (d, 3H, $J = 7$ Hz), 1.12 (d, 3H, $J = 7$ Hz), 1.17 (d, 3H, $J = 7$ Hz), 1.38 (d, 1H, $J = 6.5$ Hz), 1.75 (t, 1H, $J = 6.5$ Hz, N*H*), 2.12 (m, 1H, $J = 7.0$ Hz), 2.23 (m, 1H, $J = 7.0$ Hz), 3.86 (m, 1H, $J = 6.5$ Hz, C*H*–CH_3), 4.12 (q, 1H, $J = 6.5$ Hz, CH_2–C*H*–NH), 4.43 (dd, 1H, $J = 13.5$ and 6.5 Hz, CH*H*–CH–NH), 4.48 (dd, 1H, $J = 13.5$ and 6.5 Hz, CH*H*–CH–NH), 6.83 (t, 1H, $J = 1.5$ Hz, C*H*=CH), 6.96 (t, 1H, $J = 1.5$ Hz, CH=C*H*), 7.15–7.50 (m, 13H). ^{13}C NMR

(100 MHz, $CDCl_3$): δ 23.0, 24.3, 24.4, 24.5, 28.0, 28.1, 55.3, 57.2 (*C*H_2–CH–NH), 61.3, 121.6 (d, J^3(Ag–^{13}C) 7 Hz, *C*H=CH), 123.4 (d, J^3(Ag–^{13}C) 7 Hz, CH=*C*H), 124.1, 124.2, 126.5, 127.1, 127.2, 128.2, 128.7, 129.0, 130.4, 134.6, 139.6, 145.0, 145.5, 145.6, 181.9 (dd, J^1(^{109}Ag–^{13}C) 272 Hz and J^1(^{107}Ag–^{13}C) 237 Hz, $C_{carbene}$). Anal. Calcd for $(C_{31}H_{37}ClN_3Ag)_8(AgCl)$ (M_w = 4903.05) C, 60.75; H, 6.08; N, 6.86. Found C, 60.71; H, 6.01; N, 6.83.

4.3.4. 3-(2,6-Diisopropylphenyl)-1-[(2*S*)-2-{(*S*)-1-(*p*-methoxyphenyl)ethylamino}-2-phenyl ethyl]imidazol-2-ylidene silver chloride 23. Yield 86%, beige powder. Mixture of diastereomers (80:20). Major diastereomer: ^{1}H NMR (400 MHz, CD_2Cl_2): δ 1.08 (d, 3H, J = 6.8 Hz), 1.12 (d, 3H, J = 6.8 Hz), 1.15 (d, 3H, J = 6.6 Hz), 1.20 (d, 3H, J = 6.6 Hz), 1.37 (d, 3H, J = 6.5 Hz), 1.76 (br s, 1H, N*H*), 2.20 (m, 1H, J = 6.8 Hz), 2.30 (m, 1H, J = 6.8 Hz), 3.80–3.90 (m, 4H, O*C*H_3 and C*H*–CH_3), 4.15 (t, 1H, J = 6.5 Hz, CH_2–C*H*–Ph), 4.44 (dd, 1H, J = 13.5 and 6.5 Hz, N–CH*H*–CH–Ph), 4.51 (dd, 1H, J = 13.5 and 6.5 Hz, N–C*H*H–CH–Ph), 6.85–6.92 (m, 3H), 7.02 (s, 1H), 7.20–7.42 (m, 9H), 7.50 (t, 1H, J = 8 Hz). ^{13}C NMR (100 MHz, $CDCl_3$): δ 23.0, 24.3, 24.3, 24.4, 24.5, 28.0, 28.1, 54.6 (*C*H–CH_3), 55.2 (O*C*H_3), 57.2 (*C*H_2), 61.3 (*C*H–CH_2), 113.9, 114.0, 124.1, 127.1, 127.3, 127.5, 127.7, 128.2, 129.0, 130.4, 134.6, 137.2, 139.8, 145.5, 145.6, 158.7, 182.0 ($C_{carbene}$). HRMS (in CH_3CN, sens = 6.64 e^6): found 588.2127 $[M-Cl]^+$ ($C_{32}H_{39}{}^{107}AgN_3O$ requires 588.2144).

4.3.5. 3-*tert*-Butyl-1-[(2*S*)-2-{(*S*)-1-(phenyl)ethylamino}-2-phenyl ethyl]imidazol-2-ylidene silver chloride 24. Yield 94%, grey pearl solid. Mixture of diastereomers (85:15). Major diastereomer: ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.31 (d, 3H, J = 6.5 Hz), 1.62 (s, 9H), 1.67 (m, 1H, J = 6.5 Hz, N*H*), 3.74 (m, 1H, J = 6.5 Hz, NH–C*H*–CH_3), 4.01 (q, 1H, J = 6.5 Hz, CH_2–C*H*–NH), 4.28 (dd, 1H, J = 13.6 and 6.5 Hz, C*H*H–CH–NH), 4.39 (dd, 1H, J = 13.6 and 6.5 Hz, CH*H*–CH–NH), 6.74 (d, 1H, J = 1.5 Hz), 7.01 (d, 1H, J = 1.5 Hz), 7.05–7.40 (m, 10H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 23.0 (CH–*C*H_3), 31.7 (C(*C*H_3)$_3$), 55.1, 57.6 (*C*(CH$_3$)$_3$), 58.7 (CH_2–CH–Ph), 61.1, 118.3 (*C*H=CH), 120.2 (CH=*C*H), 126.5, 126.9, 127.1, 128.0, 128.6, 129.0, 140.0, 145.1 (the carbene carbon was not detected). Exact MS (ESI+ in CH_3CN sens = 2.30 e^8) m/e = 348.2 for $C_{23}H_{30}N_3$ $[M+H-AgCl]^+$.

4.4. Typical procedures for asymmetric allylic alkylation

Method A (THF, 20 °C): A mixture of $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ (4.3 mg, 0.012 mmol, 0.03 equiv) and silver complex (0.034 mmol, 0.085 equiv) in THF (2 mL) was stirred for 1 h at 20 °C under argon. To the mixture was added a solution of (*E*)-1,3-diphenylprop-3-en-yl acetate (100 mg, 0.4 mmol, 1 equiv) in THF (1 mL) followed by a THF (1 mL) solution of dimethyl malonate (138 μL, 1.2 mmol, 3 equiv) and NaH (1.1 mmol, 2.75 equiv). The suspension was stirred for 48 h at 20 °C. A saturated aqueous NH_4Cl solution (3 mL) was added and the mixture was extracted with ethyl acetate. The combined organic layers were dried over Na_2SO_4, filtered and concentrated. The residue was purified by column chromatography (SiO_2, pentane/Et_2O; 9/1). Enantiomeric excesses were determined by ^{1}H NMR with a chiral shift reagent Eu(hfc)$_3$ or by HPLC analysis (Chiralcel OD-H; hexane–isopropanol, 99:1; flow rate 0.5 mL/min; t_R = 27.4 min (*R*) and 29.4 min (*S*)).

Method B (CH_2Cl_2, 40 °C): A mixture of $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ (4.3 mg, 0.012 mmol, 0.03 equiv) and silver complex (0.034 mmol, 0.085 equiv) in CH_2Cl_2 (1 mL) was stirred for 1 h at 20 °C under argon. To the mixture was added a solution of (*E*)-1,3-diphenylprop-3-en-yl acetate (100 mg, 0.4 mmol, 1 equiv) in CH_2Cl_2 (1 mL) followed by a CH_2Cl_2 (3 mL) solution of dimethyl malonate (138 μL, 1.2 mmol, 3 equiv), and NaH (1.1 mmol, 2.75 equiv). The suspension was stirred for 16 h at 40 °C. The same workup as for method A was followed.

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