Tetrahedron 68 (2012) 7636–7644

Contents lists available at SciVerse ScienceDirect

Tetrahedron

journal homepage: www.elsevier.com/locate/tet

Investigation of the complexation behaviour and catalysis of IBiox-[(−)-menthyl]·HOTf

Claudia Lohre [a], Corinna Nimphius [a], Marc Steinmetz [b], Sebastian Würtz [c], Roland Fröhlich [a], Constantin G. Daniliuc [a], Stefan Grimme [b], Frank Glorius [a,*]

[a] Organisch-Chemisches Institut der Westfälischen Wilhelms-Universität Münster, Corrensstrasse 40, 48149 Münster, Germany
[b] Mulliken Center for Theoretical Chemistry, Institut für Physikalische und Theoretische Chemie, Universität Bonn, Beringstrasse 4, 53115 Bonn, Germany
[c] Euticals GmbH, Industriepark Höchst, D569, 65926 Frankfurt am Main, Germany

ARTICLE INFO

Article history:
Received 2 March 2012
Received in revised form 29 May 2012
Accepted 8 June 2012
Available online 19 June 2012

Keywords:
N-Heterocyclic carbenes
Conformation studies
Asymmetric catalysis
Palladium complex
Theoretical calculations

ABSTRACT

Herein we provide an overview on the unique properties of the sterically demanding IBiox-[(−)-menthyl]·HOTf ligand (such as flexibility and sterics) and an application of this ligand in Pd-catalyzed asymmetric intra- and intermolecular α-arylation reactions. Furthermore we demonstrate the synthesis of novel NHC–metal complexes and a new bifunctional NHC ligand whilst insight into the mechanistic mode of action of IBiox-[(−)-menthyl]·HOTf in catalysis is provided.

1. Introduction

In the last couple of years *N*-heterocyclic carbenes (NHCs)[1,2] have become an important class of organocatalysts[3] and ligands[4] in organometallic chemistry and transition-metal catalysis, due to their electron richness, their steric demand and the high stability of the metal–NHC bond structure.[2] Their widespread application as ligands in catalysis demonstrates their attractive properties.[1–5] We recently reported the synthesis of an exceedingly sterically demanding ligand: the NHC derived from IBiox-[(−)-menthyl]·HOTf (**1**).[6] The desired imidazolium salt and NHC-precursor **1** could be obtained by starting with a Bucherer reaction from commercially available, enantiopure (−)-menthone (Fig. 1).[6]

At the outset of our work, we wondered if even more sterically demanding NHC ligands would lead to new levels of reactivity of the resulting metal complexes. Herein we provide an overview on the physicochemical properties, such as flexibility and sterics of IBiox-[(−)-menthyl]·HOTf (**1**) and the application of this NHC ligand in Pd-catalyzed asymmetric intra- and intermolecular α-arylation reactions. Furthermore we present the synthesis of novel IBiox-[(−)-menthyl] derived metal complexes, the synthesis of a bifunctional IBiox-[(−)-menthyl]-derived ligand and mechanistic understanding of ligand **1** in catalysis.

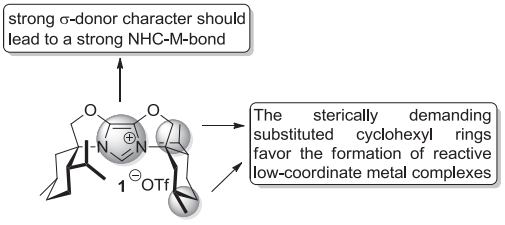


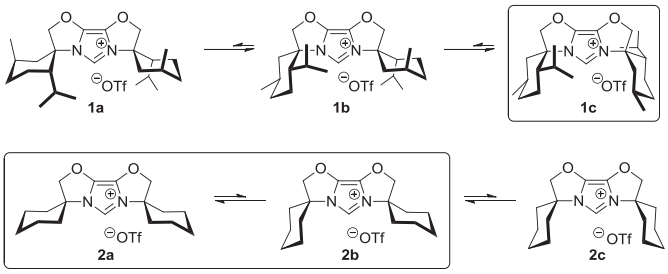
Fig. 1. Sterically demanding IBiox-[(−)menthyl]·HOTf (**1**) ligand.

2. Results and discussion

Based on the chair flip of the cyclohexyl rings the IBiox6 system **2** is structurally dynamic. It was shown that the least sterically demanding conformation (**2a**) is preferred (Scheme 1). In the (−)-menthyl-derived IBiox precursor **1** the additional ^{i}Pr/Me substituents on the cyclohexyl rings shift the equilibrium towards the most sterically demanding conformation **1c**.[7] The predominance of conformation **1c** was confirmed by NMR studies at −80 °C and rt, which show only one set of signals, and X-ray analysis. As a result, ligand **1** has an enhanced steric demand compared to IBiox6.[6,7] The preferred conformations **1c** of NHC-precursor **1** and **2a** and **2b** of the NHC-precursor IBiox6 are also evident from DFT calculations of

* Corresponding author. E-mail address: glorius@uni-muenster.de (F. Glorius).

0040-4020/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.tet.2012.06.039



Scheme 1. Chair flip properties of IBiox-[(−)-menthyl]·HOTf (**1**) and IBiox6·HOTf.

the different conformations of **1** and **2** at 193 K, 298 K (shown) and 373 K (see Supplementary data). The calculations were performed with two different dispersion corrected density functionals,[8,9,11,12] which yield qualitatively the same picture. However, for the discussion only the ΔG^{298} corrected (Figs. 2 and 4) and the ΔG^{323} corrected results at the B2PLYP-D3/QZVPP//TPSS-D3/TZVP (Figs. 2 and 3) and B2PLYP-D3/TZVPP//TPSS/TZVP (Fig. 4) were used.[8–12]

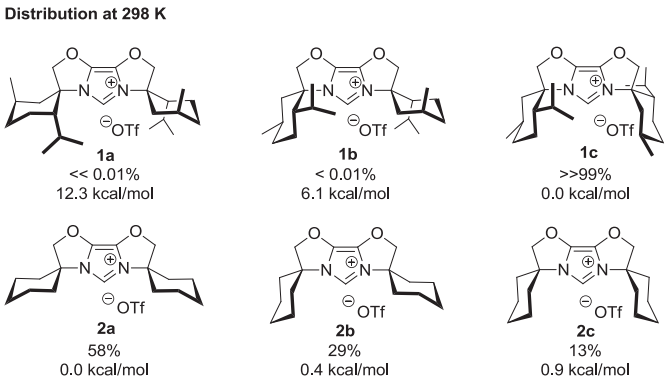
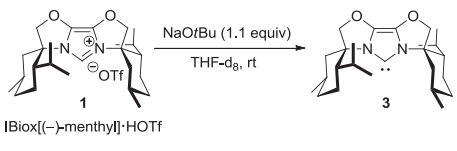


Fig. 2. Calculated relative free enthalpies of the different conformations of **1** and **2** at 298 K and the corresponding equilibrium populations.

The free carbene **3** was formed by in situ deprotonation in THF-d_8 using NaO*t*Bu as base. The indicative and characteristic signal of the carbene carbon at δ=194.6 in the ^{13}C NMR spectrum provides evidence for the formation of the free carbene and makes complexation of a metal possible. Therefore ligand precursor **1** should be able to provide interesting complexes (Scheme 2).[6]



Scheme 2. Synthesis of the free carbene of **1**.[6]

In addition, we synthesized a bifunctional NHC-ligand derived from (−)-menthone to obtain the saturated imidazolinium salt **6** (Scheme 3). Starting from the chiral aminoalcohol **4**, the imidazolinium tetrafluoroborate salt **6** was synthesized by a standard procedure whereas the ring closure of diamine **5** was carried out with NH_4BF_4 and triethyl orthoformate to obtain the desired product in 41% yield.[13]

A description of the steric demand of NHC ligands in a general way is challenging, considering the variety of *N*-substituents and the anisotropic structure of NHCs. A method to calculate the steric demand of NHC ligands was developed by Nolan, Cavallo, and coworkers.

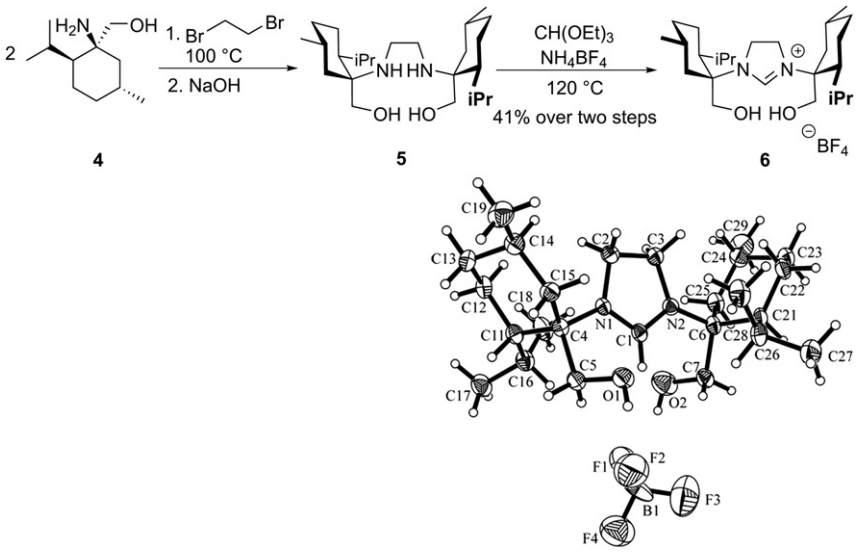
They demonstrated how to quantify the steric demand by means of the 'buried volume' (%V_{bur}) of various NHCs (Table 1).[2,14–16] For numerous X-ray structures of [(NHC)AuCl], [(NHC)AgCl], and [(NHC)CuCl] complexes the buried volume was calculated (Table 1). The buried volume for some of the most commonly used NHCs ranges from 36.5% to 47.0% (calculated from their AuCl complexes, Table 1, entries 1–5).[2,16,17]

To the best of our knowledge the chiral IBiox[(−)-menthyl], CAAC, as well as the achiral IPr* (1,3-bis[2,6-bis(diphenyl-methyl)-4-methylphenyl] imidazol-2-ylidene) and the most shielding ligand IPr** (1,3-bis[2,6-bis[(4-*tert*-butylphenyl)-methyl]-4-ethylphenyl]imidazol-2-ylidene)[14] are among the most sterically demanding monodentate carbene ligands with a buried volume range from 47.7% to 53%.[2,15b,15c,15i,17] The buried volume (%V_{bur}) for the NHC ligand derived from imidazolinium salt **6** determined from its X-ray data was found to be 37%.

Furthermore, different NHC–metal complexes from IBiox-[(−)-menthyl]·HOTf (**1**) were synthesized with coinage metals (Scheme 4). First, deprotonation of IBiox-[(−)-menthyl]·HOTf (**1**) with NaO*t*Bu in THF or CH_2Cl_2 for the free carbene formation followed by addition of the desired metal salt, stirring overnight at room temperature yielded, after column-chromatography, the desired NHC–metal complexes in good to excellent yields (Scheme 4).[6,18] We could obtain X-ray structures of all new NHC–metal complexes, which exhibit a linear conformation (Scheme 5). The calculation of the buried volume of the newly obtained complexes IBiox-[(−)-menthyl]–CuCl, IBiox-[(−)-menthyl]–AgBr and IBiox-[(−)-menthyl]–AuCl showed the well-defined dependency of the steric demand on the inserted metal species (Table 2). The results are in analogy to the results of other NHCs, where a similar decrease of the steric demand from the Cu to Ag to Au can be found.

In previous work we could already show the successful application of IBiox[(−)-menthyl]·HOTf (**1**) in the Pd-catalyzed asymmetric intramolecular α-arylation of aryl chlorides for the synthesis of 3,3-disubstituted oxindoles.[4,6,19–24] Remarkably, in the case of sterically more demanding substrates IBiox[(−)-menthyl]·HOTf (**1**) generally leads to the formation of the corresponding oxindoles with increased enantioselectivities. With synthetically more versatile *N*-benzyl-substituted substrates higher enantioselectivities are obtained compared to the *N*-methyl-substituted substrates. Even at higher temperatures (100 °C) we observed for sterically demanding substrates, good yields with remarkably high ee. This finding is another indication for the high level of rigidity of the novel NHC ligand **1**. This enables the conversion of less reactive substrates at higher temperature without significant loss of enantioselectivity (Scheme 6).

Furthermore, the palladium catalyzed α-arylation of ketones has become an established synthetic method. Whereas chiral bisphosphine ligands have been very successfully employed in intermolecular asymmetric α-arylation reactions, the use of chiral monodentate NHC ligands in these reactions is still in its infancy.[25] In 2005, the intermolecular α-arylation of ketones using an achiral NHC–palladium complex was reported by Nolan, but still, the formation of quaternary centres failed.[26] Recently we published on the enantioselective Pd/cinchona alkaloid catalyzed α-arylation between cyclic ketones and arylhalides under phosphine-free conditions.[27] We were also pleased to find that IBiox[(−)-menthyl]·HOTf (**1**) provides the reactivity needed to enable the Pd-catalyzed intermolecular α-arylation of 2-methyl-1-tetralone giving products containing a quaternary stereocenter (Scheme 7). Moreover, these products are formed with significant levels of

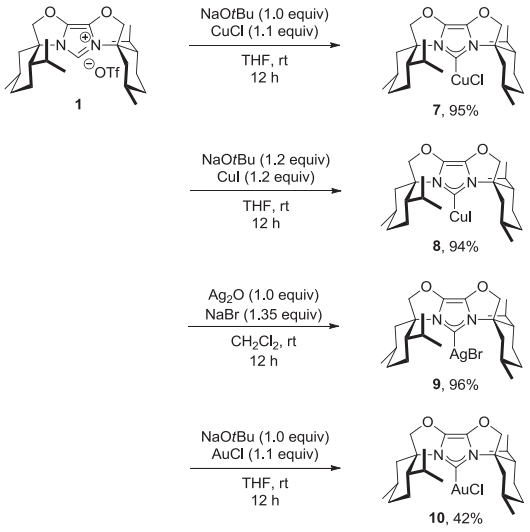


Scheme 3. Synthesis of a new chiral NHC ligand **6**.

Table 1
$\%V_{bur}$ for some of the most commonly used NHCs

Entry	NHC	$\%V_{bur}$ (Au)
1	ICy	27.4
2	IMes	36.5
3	SIMes	36.9
4	IPr	44.5
5	SIPr	47.0

Determined from X-ray structure from the NHC–Au complex (parameter: r=3.5 A, d=2.0 A, Bondi radii scaled by 1.17).



Scheme 4. Synthesis of the the IBiox[(−)-menthyl]–Cu/Ag/Au-complexes.[18]

enantioselectivity. Arguably, this represents a further successful application of the chiral NHC **1** in an intermolecular α-arylation reaction.

The role of the bulky menthyl group with the ^{i}Pr/Me group is demonstrated in the crystal structure of the Pd-complex. The location and orientation of the cyclohexyl ring is fixed by conformational locking of the ^{i}Pr/Me group that enables optimal transfer of chiral information. The complex was synthesized from [Pd(allyl)Cl]$_2$, **1** and NaO*t*Bu in THF at room temperature in good yield (Scheme 8).[29]

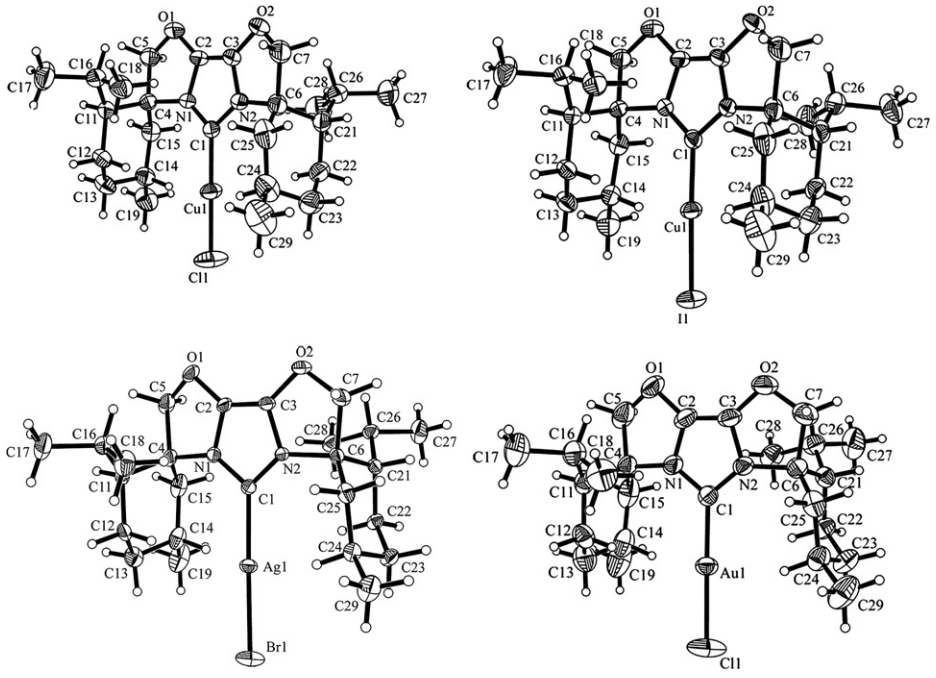
The structure of the isolated IBiox[(−)-menthyl]–Pd(allyl)Cl-complex (**13**) and its different conformations at 50 °C were determined by DFT calculations (Fig. 3). The calculated population of conformation **13c** is above 99%. These results are in line with the ones obtained by crystal structure analysis of complex **13** (not shown),[28] showing that the more sterically demanding conformation is locked. The existence of conformation **13c** is promoted by (an)agostic interactions that stabilize this conformation.

Despite the high steric demand of the IBiox[(−)-menthyl]·HOTf ligand, the corresponding unsaturated Pd species can undergo dimerization. The dimeric complex **14** was synthesized from Pd(OAc)$_2$, **1** and LiCl in THF at 100 °C. A crystal suitable for X-ray analysis could be obtained (Scheme 9). The Pd–C–NHC bond lengths obtained are 1.958 Å and 1.951 Å.

Finally, attention was turned to the aryl chloride substrates and DFT calculations revealed the mode of asymmetric induction in the α-arylation of amides. The mechanism of this reaction follows the general coupling pathway. The ligand of choice demonstrates the importance of the bulky menthyl groups. Chiral induction from this intermediate could occur during the Pd–O–enolate to Pd–C–enolate rearrangement or during reductive elimination. Both the steric and electronic properties of the ligands are important. Sterically hindered ligands render the reductive elimination more facile.[18] The B2PLYP-D3/TZVPP calculations showed that the *S*-configuraton of the Pd–C–enolate complex is preferred over the *R*-configuration by 7.5 kcal/mol, stabilized by (an)agostic interactions with the methyl group (Scheme 10; Fig. 4). New chiral NHC ligands, which provided excellent results in Pd-catalyzed α-arylation of amides reported by Kündig group revealed a diminished role of the bulkiness of their ligands for the chiral induction because the $\%V_{bur}$ for their best and less bulky ligand was 37.4%.[24]

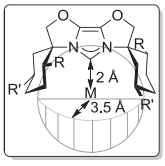
3. Conclusion

In conclusion, we have investigated the behaviour of the sterically demanding, C_2-symmetric NHC-ligand derived from IBiox[(−)-menthyl]·HOTf (**1**). The successful synthesis of a new bifunctional IBiox[(−)-menthyl] derived NHC precursor **6** could be demonstrated. Furthermore the successful application of IBiox[(−)-menthyl]·HOTf (**1**) in Pd-catalyzed asymmetric intra- and



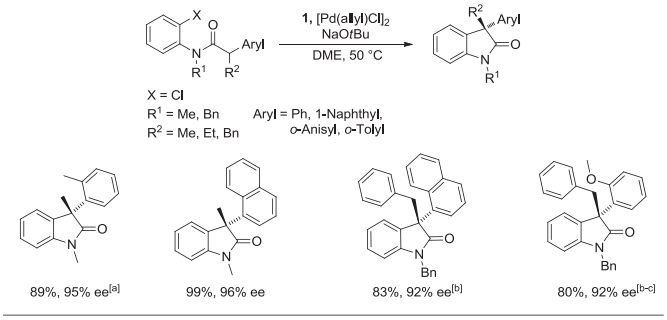
Scheme 5. X-ray structures of the [(IBiox-[(−)-menthyl])–CuCl], [(IBiox-[(−)-menthyl])–CuI], [(IBiox-[(−)-menthyl])–AgBr][6] and the [(IBiox-[(−)-menthyl])–AuCl]-complexes.

Table 2
$\%V_{bur}$ for the IBiox[(−)-menthyl]–Cu/Ag/Au-complexes



Entry	Complex	Metal	$\%V_{bur}$
1	7	Cu	51.0
2	9	Ag	49.4
3	10	Au	47.7

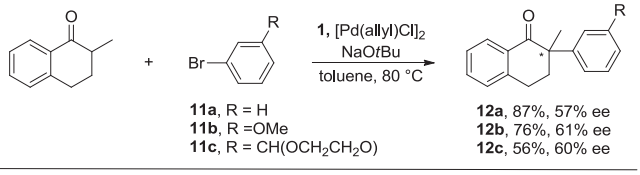
Determination of the X-ray structures from the NHC–metal-complexes (Parameter: r=3.5 Å, d=2.0 Å, Bondi radii scaled by 1.17).



General procedure: 0.3 mmol scale, NaOtBu (0.45 mmol), $[Pd(allyl)Cl]_2$ (2.5mol%), **1** (5 mol%), DME (3 mL), 50°C, 12-16 h; ee determined by chiral HPLC. [a] 80°C. [b] 90 °C; 24 h. [c] At 80 °C, the product could be obtained in 37% yield with 99% ee.

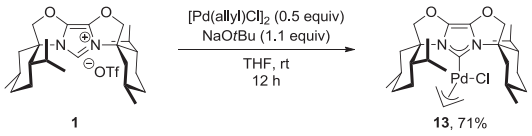
Scheme 6. Intramolecular α-arylation of aryl chlorides.

intermolecular α-arylation reactions to obtain high levels of enantioselectivity could be illustrated, revealing the unique reactivity and selectivity of this ligand system. Novel NHC–metal complexes were synthesized and DFT calculations confirmed that the asymmetric induction of the metal–ligand system is strongly linked to the presence



Reaction conditions: 2-methyl-1-tetralone (0.3 mmol), aryl bromide (0.6 mmol), NaO*t*Bu (0.6 mmol), $[Pd(allyl)Cl]_2$ (2.5 mol%), **5** (5 mol%), toluene (3 mL), 80 °C, 13-15 h; ee determined by chiral HPLC.

Scheme 7. Intermolecular α-arylation of 2-methyl-1-tetralone.



Scheme 8. Synthesis of the IBiox[(−)-menthyl]–Pd(allyl)Cl-complex.

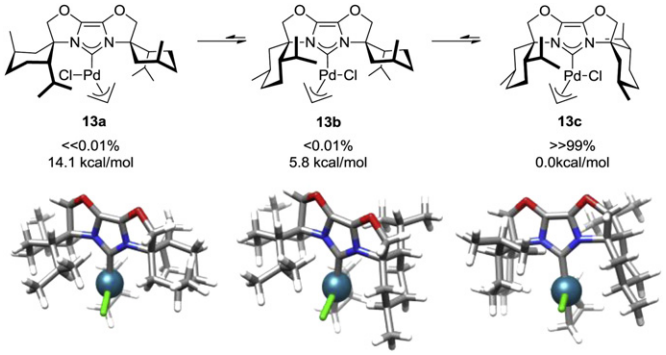
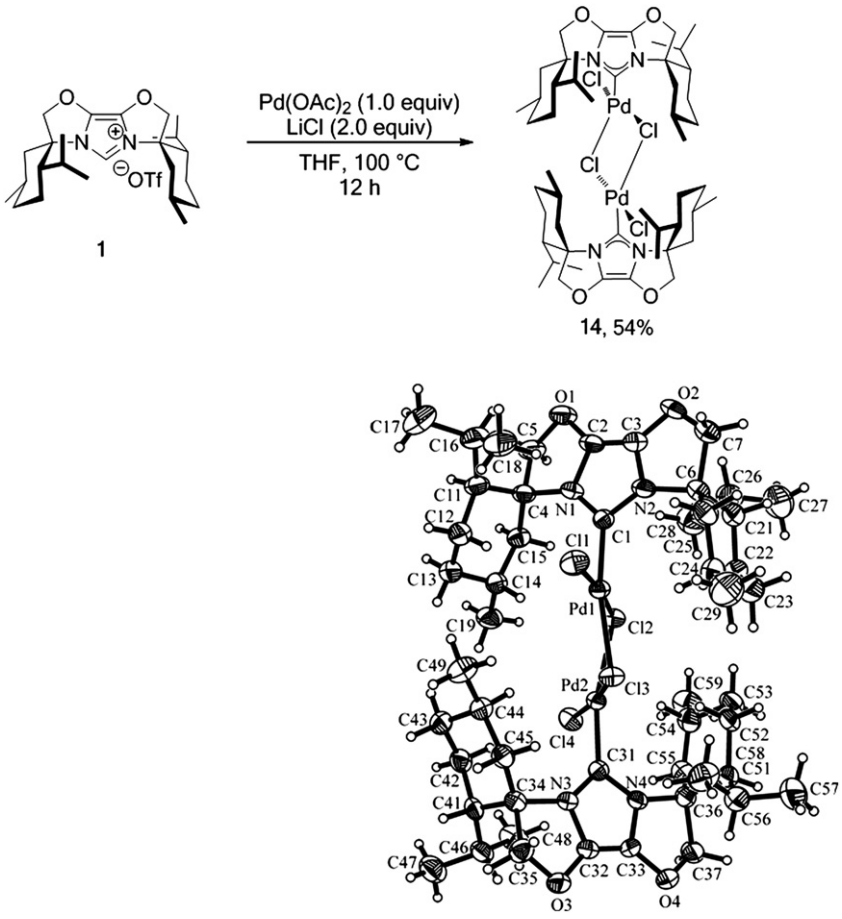
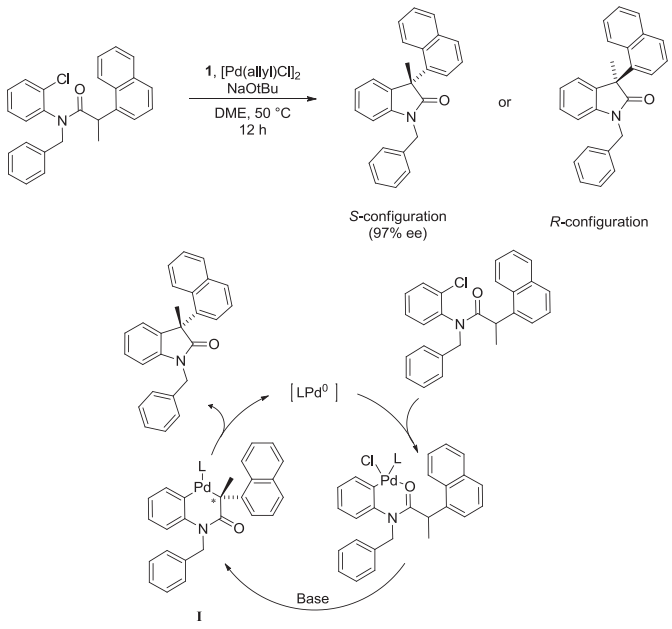


Fig. 3. Calculated relative free enthalpies of the IBiox[(−)-menthyl]–Pd(allyl)Cl-complex (**13**) at 50 °C (323 K) and the corresponding Boltzmann distributions.



Scheme 9. Synthesis of the dimeric IBiox-[(−)-menthyl]–PdCl-complex **14**.



Scheme 10. Mechanistic studies based on Hartwig's proposed catalytic cycle.

of the bulky ^{i}Pr/Me groups connected at the cyclohexyl rings and agostic interactions for stabilization effects. Further development of chiral bifunctional NHC ligands, their application in organometallic catalysis, and additional mechanistic studies are in progress.

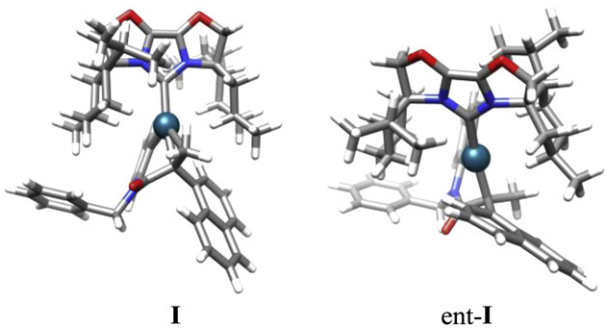


Fig. 4. Pd–C–enolate complex **I** (0.0 kcal/mol) and ent-**I** (7.5 kcal/mol) obtained by DFT calculations.

4. Experimental

4.1. General

Unless otherwise noted, all reactions were carried out under an atmosphere of argon in flame-dried glassware. The solvents used were purified by distillation over the drying agents indicated in parentheses and were transferred under argon: *n*-hexane, CH_2Cl_2, Toluene (CaH_2), THF (Na–benzophenone). Anhydrous DME was purchased from Acros Organics and stored over molecular sieves under argon. Commercially available chemicals were obtained from Acros Organics, Aldrich Chemical Co., Strem Chemicals, Alfa Aesar, ABCR and TCI Europe and used as received unless otherwise stated.

NMR-spectra were recorded on a Bruker ARX-300, AV-300 or AV-400 MHz ^{1}H and ^{13}C NMR spectra were recorded in $CDCl_3$ or in the solvent indicated. Chemical shifts (δ) are quoted in parts per million downfield of tetramethylsilane and were referenced to the residual chloroform and $CDCl_3$, ^{1}H NMR: 7.26 ppm, ^{13}C NMR: 77.00 ppm, respectively; likewise for other solvents where applicable as internal standard on the δ scale. Coupling constants (J) are quoted in Hertz. Infrared spectra were recorded on a Varian Associated FTIR 3100 Excalibur with ATR unit. The wave numbers (ν) of recorded IR-signals are quoted in cm^{-1}. ESI mass spectra were recorded on a Bruker Daltonics MicroTof. Specific rotation was measured on a Perkin Elmer 341 polarimeter at 20 °C using a quartz glass cell (100 mm path length). HPLC analysis was performed on an Agilent Technologies 1200 series HPLC with a Daicel Chemical Industries LTD chiral AD-H column. Analytical thin layer chromatography was performed on Polygram SIL G/UV254 plates. Visualization was accomplished with short wave UV light and/or $KMnO_4$ staining solution followed by gentle heating. Flash column chromatography was performed on Merck silica gel (40–63 mesh) by using standard laboratory techniques. Solvents used for flash column chromatography were distilled before use. GC/MS Spectra were recorded with an Agilent Technologies 7890A GC-system with Agilent 5975C VL MSD or 5975 inert Mass Selective Detector and a HP-5MS column (0.25 mm×30 m, Film: 0.25 μm).

4.2. Preparation of the IBiox[(−)-menthyl]–metal complexes

*4.2.1. IBiox[(−)-menthyl]–CuCl (**7**).* A Schlenk flask was charged with IBiox[(−)-menthyl]·HOTf (**1**) (500 mg, 0.91 mmol, 1.0 equiv), NaO*t*Bu (87 mg, 0.91 mmol, 1.0 equiv) and THF (20 mL). The mixture was stirred for 10 min and then CuCl (99 mg, 1.0 mmol, 1.1 equiv) was added. The resulting solution was stirred at room temperature for 12 h. The resulting mixture was filtered over Celite and washed with CH_2Cl_2 (3×20 mL). The combined filtrates were collected, and the solvent was evaporated under reduced pressure. After purification by flash chromatography (silica, CH_2Cl_2/MeOH=90:1) the pure product was obtained as a white solid (515 mg, 0.86 mmol, 95%); R_f (CH_2Cl_2/MeOH=10:1): 0.82; ^{1}H NMR (300 MHz, $CDCl_3$): δ=0.30 (d, J=6.7 Hz, 6H, 2×CH_3), 0.99–0.93 (m, 14H), 1.38–1.23 (m, 4H), 1.75–1.67 (m, 2H), 1.92–1.85 (m, 2H), 2.19–2.00 (m, 4H), 2.51–2.38 (m, 2H), 3.52–3.46 (m, 2H, CH_2), 4.41 (d, J=8.9 Hz, 2H, CH_2), 4.66 (d, J=8.9 Hz, 2H, CH_2); ^{13}C NMR (75 MHz, $CDCl_3$): δ=16.4 (CH_3), 22.4 (CH_3), 22.6 (CH_2), 24.2 (CH_3), 26.1 (CH_2), 30.1 (CH), 34.1 (CH), 45.9 (CH_2), 51.0 (CH), 67.3 (C_q), 87.8 (CH_2), 126.7 (C_q), 154.1 (C_q); ESI-MS: calculated for $[C_{25}H_{40}N_2O_2ClCuNa]^+$: 521.1967, found: 521.1954; Element. Anal. calcd for $C_{25}H_{40}ClCuN_2O_2$: C, 60.10; H, 8.07; N, 5.61; found: C, 59.97; H, 8.12; N, 5.79; ATR-FTIR (cm^{-1}): 2955, 2929, 2871, 1748, 1476, 1431, 1300, 1202, 976, 937, 851, 687, 568; $[\alpha]_D^{20}$=+85 (c=0.99 in $CHCl_3$). The structure was determined by X-ray analysis.

*4.2.2. IBiox[(−)-menthyl]–CuI (**8**).* A Schlenk flask was charged with IBiox[(−)-menthyl]·HOTf (**1**) (1.0 g, 1.82 mmol, 1.0 equiv), NaOtBu (210.0 mg, 2.18 mmol, 1.2 equiv) and THF (40 mL). The mixture was stirred for 10 min and then CuI (415 mg, 2.18 mmol, 1.2 equiv) was added. The resulting solution was stirred at room temperature for 12 h. The resulting mixture was filtered over Celite and washed with CH_2Cl_2 (3×40 mL). The combined filtrates were collected, and the solvent was evaporated under reduced pressure. After purification by flash chromatography (silica, CH_2Cl_2/MeOH=90:1) the pure product was obtained as a white solid (1.011 g, 1.71 mmol, 94%); R_f (CH_2Cl_2/MeOH=10:1): 0.78; ^{1}H NMR (300 MHz, $CDCl_3$): δ=0.32 (d, J=6.9 Hz, 6H, 2×CH_3), 0.95–0.86 (m, 14H), 1.37–1.24 (m, 4H), 1.72–1.66 (m, 2H), 1.91–1.84 (m, 2H), 2.17–2.00 (m, 4H), 2.45–2.35 (m, 2H), 3.52–3.47 (m, 2H, CH_2), 4.43 (d, J=8.7 Hz, 2H, CH_2), 4.68 (d, J=8.7 Hz, 2H, CH_2); ^{13}C NMR (75 MHz, $CDCl_3$): δ=16.4 (CH_3), 22.0 (CH_3), 22.3 (CH_2), 24.2 (CH_3), 26.1 (CH_2), 30.1 (CH), 33.8 (CH), 45.8 (CH_2), 50.7 (CH), 67.5 (C_q), 87.8 (CH_2), 126.6 (C_q), 155.9 (C_q); ESI-MS: calculated for $[C_{25}H_{40}N_2O_2CuINa]^+$: 613.1323, found: 613.1326; ATR-FTIR (cm^{-1}): 2952, 2853, 2349, 2154, 1753, 1475, 1434, 1390, 1369, 1299, 1274, 1204, 1155, 1105, 1022, 1002, 987, 975, 936, 924, 880, 851, 813, 685, 641; $[\alpha]_D^{20}$=+63 (c=1.11 in $CHCl_3$). The structure was determined by X-ray analysis.

*4.2.3. IBiox[(−)-menthyl]–AgBr (**9**).* A Schlenk flask was charged with IBiox[(−)-menthyl]·HOTf (**1**) (150 mg, 0.27 mmol, 1.0 equiv), Ag_2O (63 mg, 0.27 mmol, 1.0 equiv), NaBr (37 mg, 0.36 mmol, 1.35 equiv) and CH_2Cl_2 (6 mL) was added. The resulting solution was stirred in the dark at rt for 12 h. The resulting precipitate was filtered over Celite and washed with CH_2Cl_2 (3×20 mL). The combined filtrates were collected, and the solvent was reduced under pressure. After crystallization with CH_2Cl_2/*n*-hexane the pure product was obtained as colourless crystals (151 mg, 0.26 mmol, 96%); R_f (CH_2Cl_2/MeOH=10:1): 0.87; ^{1}H NMR (400 MHz, $CDCl_3$): δ=0.30 (d, J=6.8 Hz, 6H, 2×CH_3), 0.95–0.93 (m, 14H), 1.39–1.21 (m, 4H), 1.73–1.67 (m, 2H), 1.95–1.89 (m, 2H), 2.15–2.03 (m, 4H), 2.35–2.20 (m, 2H), 3.32–3.16 (m, 2H, CH_2), 4.42 (d, J=9.4 Hz, 2H, CH_2), 4.65 (d, J=9.4 Hz, 2H, CH_2); ^{13}C NMR (100 MHz, $CDCl_3$): δ=16.6 (CH_3), 22.7 (CH_3), 22.8 (CH_2), 24.4 (CH_3), 26.2 (CH), 30.5 (d, J=3.3 Hz, CH), 34.1 (CH_2), 45.8 (CH_2), 51.5 (CH), 67.8 (C_q), 88.3 (CH_2), 127.5 (d, ^3J (^{13}C, ^{109}Ag)=6.6 Hz, C_q), 156.9 (dd, J (^{13}C, ^{109}Ag)= 275.9 Hz, J (^{13}C, ^{107}Ag)=240.2 Hz C_q); ESI-MS: calculated for $[C_{25}H_{40}N_2O_2AgBrNa]^+$: 609.1216, found: 609.1215; Element. Anal. calcd for $C_{25}H_{40}AgBrN_2O_2$: C, 51.03; H, 6.85; N, 4.76; found: C, 51.01; H, 6.92; N, 4.82; ATR-FTIR (cm^{-1}): 2958, 2924, 2857, 1754, 1433, 1297, 976, 937, 806, 741, 686, 655, 602, 596; $[\alpha]_D^{20}$=+71 (c=0.28 in $CHCl_3$). The structure was determined by X-ray analysis.

*4.2.4. IBiox[(−)-menthyl]–AuCl (**10**).* A Schlenk flask was charged with IBiox[(−)-menthyl]·HOTf (**1**) (198 mg, 0.36 mmol, 1.0 equiv), NaOtBu (35 mg, 0.36 mmol, 1.0 equiv) and THF (4 mL). The mixture was stirred for 10 min and then Au(I)Cl (93 mg, 0.40 mmol, 1.1 equiv) was added. The resulting solution was stirred at room temperature for 12 h. The resulting mixture was filtered over Celite and washed with CH_2Cl_2 (3×5 mL). The combined filtrates were collected, and the solvent was evaporated under reduced pressure. After purification by short flash chromatography (silica, CH_2Cl_2) the pure product was obtained as a white solid (97 mg, 0.15 mmol, 42%); R_f (CH_2Cl_2/MeOH=10:1): 0.90; ^{1}H NMR (300 MHz, CD_2Cl_2): δ=0.39 (d, J=6.7 Hz, 6H, 2×CH_3), 0.97–0.91 (m, 14H), 1.25–1.16 (m, 2H), 1.46–1.40 (m, 2H), 1.73–1.68 (m, 2H), 2.09–1.94 (m, 6H), 2.84–2.70 (m, 2H), 3.92–3.84 (m, 2H), 4.44 (d, J=8.9 Hz, 2H, CH_2), 4.65 (d, J=8.9 Hz, 2H, CH_2), ^{13}C NMR (100 MHz, CD_2Cl_2): δ=16.9 (CH_3); 22.5 (CH_3), 22.9 (CH_2), 24.5 (CH_3), 26.7 (CH_2), 29.6 (CH), 34.8 (CH), 45.7 (CH_2), 52.1 (CH), 69.6 (C_q), 89.1 (CH_2), 127.6 (C_q), 148.8 (C_q), ESI-MS: calculated for $[C_{25}H_{40}N_2O_2AuClNa]^+$: 655.2336, found: 655.2335; Element. Anal. calcd for $C_{25}H_{40}N_2O_2AuCl$: C, 47.43; H, 6.37; N, 4.43; found: C, 47.52; H, 6.45; N, 4.24; $[\alpha]_D^{20}$=+80 (c=0.98 in $CHCl_3$). The structure was determined by X-ray analysis. (Moisture- and air sensitive compound was handled under an argon atmosphere).

*4.2.5. IBiox[(−)-menthyl]–Pd(allyl)Cl (**13**).* A Schlenk flask was charged with IBiox[(−)-menthyl]·HOTf (**1**) (250 mg, 0.45 mmol, 1.0 equiv), NaOtBu (48 mg, 0.50 mmol, 1.1 equiv), $[Pd(allyl)Cl]_2$ (83 mg, 0.23 mmol, 0.50 equiv) and THF (4.7 mL). After stirring overnight at room temperature the resulting mixture was filtered over Celite and washed with CH_2Cl_2 (3×10 mL). The combined filtrates were collected, and the solvent was evaporated under reduced pressure. After purification by flash chromatography (silica, CH_2Cl_2/MeOH=100:1→50:1) the pure product was obtained as a yellow solid (186 mg, 0.32 mmol, 71%); R_f (CH_2Cl_2/MeOH=10:1): 0.76; ESI-MS: calculated for $[C_{28}H_{45}N_2O_2Pd]^+$: 547.2521, found:

547.2523; ATR-FTIR (cm^{-1}): 2948, 2868, 1782, 1459, 1421, 1390, 1368, 1336, 1310, 1291, 1229, 1200, 1190, 1151, 1108, 1040, 978, 935, 879, 842, 806, 765, 687, 667; $[\alpha]_D^{20}$=+77 (c=0.77 in $CHCl_3$). The strucutre of **13** was confirmed by single-crystal X-ray analysis but the X-ray data were not good enough for publication.

*4.2.6. Imidazolinium tetrafluoroborate salt (**6**).* ((1*S*,2*S*,5*R*)-1-Amino-2-isopropyl-5-methylcyclohexyl)methanol (2.7 g, 14,6 mmol, 2.0 equiv) was mixed in a pressure vessel with 1,2-dibromoethane (625 μL, 7.3 mmol, 1.0 equiv) and stirred at 100 °C overnight under argon. The resulting solid was taken up with aqueous NaOH (1 M) and CH_2Cl_2 and the aqueous phase was extracted with CH_2Cl_2 (3×30 mL). The combined organic layers were dried over Na_2SO_4 and concentrated in vacuo. The resulting diamine (1.76 g, red–brownish oil) was used without further purification. To the diamine (1.7 g, 4.4 mmol, 1.0 equiv) NH_4BF_4 (461 mg, 4.4 mmol, 1.0 equiv) and triethyl orthoformate (750 μL, 4.4 mmol, 1.0 equiv) were added and the mixture was stirred at 120 °C overnight. After cooling to room temperature and removal of EtOH the crude product was purified by flash chromatograghy (silica, CH_2Cl_2/MeOH=40:1). The pure product was obtained as a white solid (1.79 mmol, 41% for both steps); R_f (CH_2Cl_2/MeOH=10:1): 0.61; ^{1}H NMR (300 MHz, $CDCl_3$): δ=0.86 (d, J=6.8 Hz, 6H, CH_3), 0.95 (dd, J=6.2 Hz, J=14.0 Hz, 14H), 1.10–1.28 (m, 4H), 1.32–1.49 (m, 4H), 1.72–1.78 (m, 2H), 1.85–1.89 (m, 2H), 1.95–2.05 (m, 2H), 2.26–2.31 (m, 2H), 3.43 (d, J=11.8 Hz, 2H), 3.57 (brs, 2H, OH), 4.08–4.13 (m, 6H), 7.79 (s, 1H, NHCN); ^{13}C NMR (75 MHz, $CDCl_3$): δ=19.0, 22.1, 24.0, 25.8, 26.6, 27.7, 35.1, 42.3, 47.8, 49.1, 66.0, 66.6, 158.4 (NHCN); ESI-MS: calculated for $[C_{25}H_{47}N_2O_2]^+$: 407.3632, found: 407.3640; ATR-FTIR (cm^{-1}):=2951, 2869, 2396, 1613, 1459, 1367, 1279, 1205, 1156, 1049, 999, 899, 760, 649, 594, 552, 523, 515, 496; $[\alpha]_D^{20}$=+17.4 (c=0.975 in $CHCl_3$). The structure was determined by X-ray analysis.

*4.2.7. IBiox[(−)menthyl]$_2$–PdCl-complex (**14**).* A Young Teflon® tube was charged under argon with IBiox[(−)menthyl]·HOTf (**1**) (500 mg, 0.91 mmol, 1.0 equiv), $Pd(OAc)_2$ (204 mg, 0.91 mmol, 1.0 equiv), LiCl (77 mg, 1.82 mmol, 2.0 equiv) and THF (5 mL). The solution was stirred overnight at 100 °C. After cooling to room temperature the residue was taken up with CH_2Cl_2 (30 mL) and washed with water (1×15 mL). The aqueous layer was extracted with CH_2Cl_2 (2×10 mL) and the combined organic layers were washed with water (1×15 mL), dried over Na_2SO_4 and concentrated in vacuo. The crude product was purified by flash chromatography (silica, CH_2Cl_2/MeOH=40:1). The product was obtained as an orange solid (0.49 mmol, 54%); R_f (CH_2Cl_2/MeOH 10:1)=0.84; ^{1}H NMR (400 MHz, CD_2Cl_2): δ=0.22 (d, J=6.6 Hz, 6H, 2×CH_3), 0.38 (d, J=6.8 Hz, 6H, 2×CH_3), 0.93–1.30 (m, 32H), 1.48–1.57 (m, 4H), 1.73–1.90 (m, 4H), 2.17–2.75 (m, 14H), 3.14–3.23 (m, 2H), 4.27–4.55 (m, 8H), 4.85–4.87 (m, 2H), 5.32–5.33 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ=130.64 (s, C_q), 129.80 (s, C_q), 114.81 (s, 2 x C_q), 88.87 (s, CH_2), 88.83 (s, CH_2), 71.95 (s, C_q), 71.18 (s, C_q), 55.51 (s, CH), 43.10 (s, CH_2), 41.63 (s, CH_2), 35.96 (s, CH_2), 35.49 (s, CH_2), 31.78 (s, CH), 31.12 (s, CH), 26.21 (s, CH), 26.19 (s, CH), 24.61 (s, CH_3), 24.55 (s, CH_3), 23.19 (s, CH_2), 23.13 (s, CH_3), 22.81 (s, CH_3), 22.06 (s, CH_2), 17.97 (s, CH_3), 17.51 (s, CH_3); ESI-MS: calculated for $[C_{25}H_{40}N_2O_2Cl_2PdNa]^+$: 601.1396, found: 601.1383, Element. Anal. calcd for $C_{50}H_{80}N_4O_4Cl_4Pd_2 \cdot CH_2Cl_2$: C 49.37, H 6.66, N 4.52, found: C 49.65, H 6.75, N 4.46; ATR-FTIR (cm^{-1}):=2362, 2339, 1461, 980, 935, 878, 853, 686, 668, 589, 569, 561, 528, 512, 499. The structure was determined by X-ray analysis.

4.3. Intermolecular α-arylation of 2-methyl-1-tetralone

4.3.1. General procedure for the synthesis of 2-aryl-2-methyl-1-tetralones. $[Pd(allyl)Cl]_2$ (2.7 mg, $7.5\cdot10^{-4}$ mmol, 2.5 mol %), IBiox[(−)-menthyl]·HOTf (**1**) (8 mg, $1.5\cdot10^{-3}$ mmol, 5 mol %), NaO*t*Bu (58 mg, 0.6 mmol, 2 equiv) was combined in a pressure vessel and suspended in toluene (3 mL). After addition of the arylhalide (0.6 mmol, 2.0 equiv), the 2-methyl-1-tetralone (48 mg, 0.3 mmol, 1.0 equiv) was added and the resulting mixture stirred at 80 °C for 12–16 h until all starting material was consumed (GC/MS). After completion the mixture was filtered through a short plug of silica, diluted with EtOAc (50 mL) and the solvents were evaporated. The crude material was dissolved in a small amount of CH_2Cl_2, adsorbed on silica and purified by flash chromatography (silica, pentane/EtOAc).

4.3.2. Characterization of the products.

*4.3.2.1. 2-Methyl-2-phenyl-3,4-dihydronaphthalen-1(2H)-one (**12a**).* Following the general procedure, 2-methyl-1-tetralone (48 mg, 0.3 mmol, 1.0 equiv) was reacted with bromobenzene (63 μL, 0.6 mmol, 2.0 equiv) to obtain the title compound after flash chromatography (silica, pentane/EtOAc=50:1) as pale yellow oil (62 mg, 0.24 mmol, 87%); R_f (pentane/EtOAc=10:1): 0.70; ^{1}H NMR (400 MHz, $CDCl_3$): δ=1.53 (s, 3H), 2.23–2.30 (m, 1H), 2.62 (td, J=4.0 Hz, J=14.0 Hz, 1H), 2.81–2.85 (m, 2H), 7.11 (d, J=7.6 Hz, 1H), 7.17–7.23 (m, 3H), 7.25–7.33 (m, 3H), 7.42 (dt, J=1.5 Hz, J=7.5 Hz, 1H), 8.15 (dd, J=1.2 Hz, J=7.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ=26.1, 27.0, 36.2, 50.5, 126.3, 2×126.6, 127.9, 128.5, 128.6, 132.7, 133.1, 142.0, 143.5, 201.3; GC–MS t_R (method 50_40): 9.2 min; MS-EI: m/z(%)=236 (41), 221 (5), 131 (17), 118 (100), 90 (26); 57% ee (Chiracel AD-H column, n-hexane/i-PrOH=99:1, 1.0 mL/min, 254 nm; t_R=8.92 min and 10.19 min (major)); $[\alpha]_D^{20}$=+136 (c=0.635 in $CHCl_3$).

*4.3.2.2. 2-(3-Methoxyphenyl)-2-methyl-3,4-dihydronaphthalen-1(2H)-one (**12b**).* Following the general procedure, 2-methyl-1-tetralone (48 mg, 0.3 mmol, 1.0 equiv) was reacted with 3-bromoanisole (75 μL, 0.6 mmol, 2.0 equiv) to obtain the title compound after flash chromatography (silica, pentane/EtOAc=50:1) as pale yellow oil (61 mg, 0.23 mmol, 76%); R_f (pentane/EtOAc=10:1): 0.47; ^{1}H NMR (400 MHz, $CDCl_3$): δ=1.52 (s, 3H), 2.22–2.29 (m, 1H), 2.59 (td, J=4.1 Hz, J=14.0 Hz, 1H), 2.77–2.91 (m, 2H), 3.74 (s, 3H), 6.72–6.80 (m, 3H), 7.11 (d, J=7.6 Hz, 1H), 7.19 (t, J=8.0 Hz, 1H), 7.30 (t, J=7.5 Hz, 1H), 7.41 (dt, J=1.5 Hz, J=7.5 Hz, 1H), 8.14 (dd, J=1.2 Hz, J=7.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ=26.1, 27.0, 36.2, 50.5, 55.1, 111.4, 112.9, 118.8, 126.5, 127.9, 128.6, 129.5, 132.7, 133.1, 143.6, 143.7, 159.7, 201.1; GC–MS t_R (method 50_40): 9.8 min; MS-EI: m/z(%)=266 (50), 251 (8), 131 (21), 118 (100), 90 (39); ESI-MS: calculated for: $[C_{18}H_{18}O_2Na]^+$: 289.1199, found: 289.1198; 61% ee (Chiracel AD-H column, n-hexane/i-PrOH=99:1, 1.0 mL/min, 254 nm; t_R=14.08 min and 15.02 min (major)); $[\alpha]_D^{20}$=+147 (c=0.695 in $CHCl_3$); ATR-FTIR (cm^{-1}):=3065, 2928, 2836, 1680, 1600, 1487, 1454, 1289, 1260, 1221, 1046, 748, 702.

*4.3.2.3. 2-(3-(1,3-Dioxolan-2-yl)phenyl)-2-methyl-3,4-dihydronaphthalen-1(2H)-one (**12c**).* Following the general procedure, 2-methyl-1-tetralone (48 mg, 0.3 mmol, 1.0 equiv) was reacted with 3-bromobenzaldehyde- ethylenacetal (137 mg, 0.6 mmol, 2 equiv) to obtain the title compound after flash chromatography (silica, pentane/EtOAc=5:1) as yellowish oil (52 mg, 0.17 mmol, 56%); R_f (pentane/EtOAc=10:3): 0.48; ^{1}H NMR (400 MHz, $CDCl_3$): δ=1.53 (s, 3H), 2.22–2.30 (m, 1H), 2.64 (td, J=4.0 Hz, J=14.0 Hz, 1H), 2.81–2.85 (m, 2H), 3.98–4.04 (m, 2H), 4.05–4.11 (m, 2H), 5.75 (s, 1H), 7.10 (d, J=7.6 Hz, 1H), 7.18 (td, J=1.7 Hz, J=7.8 Hz, 1H), 7.25–7.34 (m, 3H), 7.37–7.43 (m, 2H), 8.14 (dd, J=1.1 Hz, J=7.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ=26.0, 27.0, 36.0, 50.4, 2× 65.2, 103.6, 124.4, 124.8, 126.5, 127.4, 127.9, 2×128.6, 132.6, 133.1, 138.1, 142.2, 143.5, 201.1; GC–MS t_R (method 50_40): 11.1 min; MS-EI: m/z(%)= 308 (15), 162 (22), 149 (30), 118 (100), 90 (48), 73 (25); 60% ee (Chiracel AD-H column, n-hexane/i-PrOH=99:1, 1.0 mL/min, 254 nm; t_R=29.55 min and 37.21 min (major)); $[\alpha]_D^{20}$=+138 (c=0.48 in $CHCl_3$).

4.4. Computational details

All calculations were carried out with the TURBOMOLE 6.3 program package.[30] The optimizations were performed with the TPSS[9] density functional together with the Ahlrichs' type triple-ζ basis set def2-TZVP.[10] For the single-point calculations the double hybrid functional B2PLYP,[8] the triple-ζ basis set def2-TZVPP[10] (for the *R*- and *S*-configuration of the Pd–O–enolate) and the large quadruple-ζ basis set def2-QZVPP[10] (in all other cases) were employed. In the case of the TPSS calculations the resolution of identity (RI-J) approximation[31] were applied. For the DFT part of B2PLYP the RI-JK approximation[32] was adapted and for the perturbative part the RI approximation[33] was used as well. All auxiliary basis sets were taken from the TURBOMOLE basis set library.[34] In all calculations the recently developed DFT-D3[11] together with the Becke–Johnson (BJ) damping function[12] was added, as indicated by the appended '-D3' to the functional name. Furthermore, to simulate solvent effects, COSMO was used in all calculations with a dielectric constant of ε=2.37 (toluene). The harmonic vibrational frequencies were obtained as numerical derivatives of analytically calculated gradients employing a modified version of the program SNF11.[35] This was done at the TPSS level only and the derived ΔG^{298} (structures **1** and **2**) as well as the ΔG^{323} (structure **13**) values were also used for B2PLYP. For structure **13a** and the *R*-configuration we obtained one imaginary vibrational frequency of *i*13 cm^{-1} and *i*9 cm^{-1}, respectively. Inspection of the corresponding normal modes indicates them as a typical numerical artefact of the numerical quadrature of the exchange-correlation energy in DFT. These vibrational frequencies were not considered in the statistical thermochemistry calculations.

4.5. X-ray data

X-ray diffraction: Data sets were collected with a Nonius KappaCCD diffractometer. Programs used: data collection, COLLECT (Nonius B.V., 1998); data reduction Denzo-SMN (Z. Otwinowski, W. Minor, *Methods Enzymol.* **1997**, *276*, 307–326); absorption correction, Denzo (Z. Otwinowski, D. Borek, W. Majewski, W. Minor, *Acta Crystallogr.* **2003**, *A59*, 228–234); structure solution SHELXS-97 (G. M. Sheldrick, *Acta Crystallogr.* **1990**, *A46*, 467–473); structure refinement SHELXL-97 (G. M. Sheldrick, *Acta Crystallogr.* **2008**, *A64*, 112–122) and graphics, XP (BrukerAXS, 2000). *R*-values are given for observed reflections, and wR^2 values are given for all reflections.

Exceptions and special features: Compound **6** crystallized with two independent molecules per asymmetric unit. For the BF_4 anions in compound **6** several restraints (ISOR and SADI) were used in order to improve refinement stability. Compound **14** present a disordered over two positions dichloromethane molecule. Several restraints (SADI, SIMU and SAME) were used in order to improve refinement stability.

X-ray crystal structure analysis of **6**: formula $C_{25}H_{47}BF_4N_2O_2$, M=494.46, colourless crystal, 0.30 x 0.12 x 0.03 mm, a=25.0708(19), b=8.0756(9), c=29.3808(9) Å, β=111.909(4)°, V=5518.9(8) Å^3, ρ_{calcd}=1.190 g cm^{-3}, μ=0.763 mm^{-1}, empirical absorption correction ($0.803 \le T \le 0.977$), Z=8, monoclinic, space group *C*2 (No. 5), λ=1.54,178 Å, T=223(2) K, ω and φ scans, 22,371 reflections collected ($\pm h$, $\pm k$, $\pm l$), [(sinθ)/λ]=0.60 $Å^{-1}$, 8361 independent (R_{int}=0.073) and 5994 observed reflections [$I>2\sigma(I)$], 631 refined parameters, R=0.103, wR^2=0.309, max. (min.) residual electron density 1.11 (−0.57) e $Å^{-3}$, hydrogen atoms calculated and refined as riding atoms. Flack parameter was refined to 0.4 (5).

X-ray crystal structure analysis of **7**: formula $C_{25}H_{40}ClCuN_2O_2$, M=499.58, colourless crystal, 0.30×0.25×0.25 mm, a=10.8800 (2), b=13.1868(3), c=17.6268(2) Å, V=2528.96(8) Å^3, ρ_{calcd}=1.312 g cm^{-3}, μ=0.992 mm^{-1}, empirical absorption correction ($0.755 \le T \le 0.789$), Z=4, orthorhombic, space group $P2_12_12_1$ (No. 19), λ=0.71,073 Å, T=223(2) K, ω and φ scans, 17,065 reflections collected ($\pm h$, $\pm k$, $\pm l$), [(sinθ)/λ]=0.60 $Å^{-1}$, 5860 independent (R_{int}=0.059) and 5070 observed reflections [$I>2\sigma(I)$], 286 refined parameters, R=0.033, wR^2=0.079, max. (min.) residual electron density 0.36 (−0.32) e $Å^{-3}$, hydrogen atoms calculated and refined as riding atoms. Flack parameter was refined to −0.006(9).

X-ray crystal structure analysis of **8**: formula $C_{25}H_{40}CuIN_2O_2$, M=591.03, colourless crystal, 0.27×0.15×0.14 mm, a=10.6305 (1), b=12.9892(2), c=18.7584(3) Å, V=2590.19(6) Å^3, ρ_{calcd}=1.516 g cm^{-3}, μ=2.058 mm^{-1}, empirical absorption correction ($0.606 \le T \le 0.761$), Z=4, orthorhombic, space group $P2_12_12_1$ (No. 19), λ=0.71,073 Å, T=223(2) K, ω and φ scans, 21,337 reflections collected ($\pm h$, $\pm k$, $\pm l$), [(sinθ)/λ]=0.60 $Å^{-1}$, 6206 independent (R_{int}=0.053) and 5973 observed reflections [$I>2\sigma(I)$], 286 refined parameters, R=0.032, wR^2=0.078, max. (min.) residual electron density 0.36 (−0.45) e $Å^{-3}$, hydrogen atoms calculated and refined as riding atoms. Flack parameter was refined to −0.027(16).

X-ray crystal structure analysis of **10**: formula $C_{25}H_{40}AuClN_2O_2$, M=663.01, colourless crystal, 0.45×0.30×0.25 mm, a=10.8960 (1), b=12.9531(2), c=18.2371(2) Å, V=2573.93(5) Å^3, ρ_{calcd}=1.634 g cm^{-3}, μ=5.842 mm^{-1}, empirical absorption correction (0.178 $\le T \le$0.323), Z=4, orthorhombic, space group $P2_12_12_1$ (No. 19), λ=0.71,073 Å, T=223(2) K, ω and φ scans, 27,524 reflections collected ($\pm h$, $\pm k$, $\pm l$), [(sinθ)/λ]=0.60 $Å^{-1}$, 7785 independent (R_{int}=0.059) and 7056 observed reflections [$I>2\sigma(I)$], 287 refined parameters, R=0.028, wR^2=0.060, max. (min.) residual electron density 0.97 (−0.95) e $Å^{-3}$, hydrogen atoms calculated and refined as riding atoms. Flack parameter was refined to −0.014(13).

X-ray crystal structure analysis of **14**: formula $C_{51}H_{82}Cl_6N_4O_4Pd_2$, M=1240.71, yellow crystal, 0.30×0.20×0.17 mm, a=11.7442(1), b=15.4845(2), c=31.3452(5) Å, V=5700.22(13) Å^3, ρ_{calcd}=1.446 g cm^{-3}, μ=0.957 mm^{-1}, empirical absorption correction ($0.762 \le T \le 0.854$), Z=4, orthorhombic, space group $P2_12_12_1$ (No. 19), λ=0.71,073 Å, T=223(2) K, ω and φ scans, 32,618 reflections collected ($\pm h$, $\pm k$, $\pm l$), [(sinθ)/λ]=0.60 $Å^{-1}$, 12,851 independent (R_{int}=0.064) and 12,004 observed reflections [$I>2\sigma(I)$], 629 refined parameters, R=0.052, wR^2=0.116, max. (min.) residual electron density 0.91 (−0.84) e $Å^{-3}$, hydrogen atoms calculated and refined as riding atoms. Flack parameter was refined to −0.1(3).

Acknowledgements

This paper is dedicated to Prof. Manfred T. Reetz on the occasion of receiving the Tetrahedron Award 2011. We thank Dr. Thomas Dröge and Cornelia Weitkamp for experimental support and discussions and Dr. Klaus Bergander for excellent NMR support (all WWU Münster). The Deutsche Forschungsgemeinschaft (GL 349 1-4 and the IRTG Münster-Nagoya) is gratefully acknowledged for financial support. The research of F.G. was supported by the Alfried Krupp Prize for Young University Teachers of the Alfried Krupp von Bohlen und Halbach Foundation.

Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tet.2012.06.039.

References and notes

1. (a) Arduengo, A. J., III. *Acc. Chem. Res.* **1999**, *32*, 913–921; (b) Bourissou, D.; Guerret, O.; Gabbai, F. P.; Bertrand, G. *Chem. Rev.* **2000**, *100*, 39–92; (c) Hahn, F. E.; Jahnke, M. C. *Angew. Chem., Int. Ed.* **2008**, *47*, 3122–3172.
2. For a review on the physicochemical properties of NHCs, see: Dröge, T.; Glorius, F. *Angew. Chem., Int. Ed.* **2010**, *49*, 6940–6953.
3. (a) Enders, D.; Niemeier, O.; Henseler, A. *Chem. Rev.* **2007**, *107*, 5606–5655; (b) Phillips, E. M.; Chan, A.; Scheidt, K. A. *Aldrichimica Acta* **2009**, *42*, 55–66; (c) Moore, J. L.; Rovis, T. *Top. Curr. Chem.* **2010**, *291*, 77–144; (d) Vora, H. U.; Rovis, T. *Aldrichimica Acta* **2011**, *44*, 3–11; (e) Hirano, K.; Piel, I.; Glorius, F. *Chem. Lett.* **2011**, *40*, 786–791; (f) Nair, V.; Menon, R. S.; Biju, A. T.; Sinu, C. R.; Paul, R. R.;

Jose, A.; Sreekumar, V. *Chem. Soc. Rev.* **2011**, *40*, 5336–5346; (g) Biju, A. T.; Kuhl, N.; Glorius, F. *Acc. Chem. Res.* **2011**, *44*, 1182–1195; (h) Chiang, P.-C.; Bode, J. W. *TCI MAIL* **2011**, *149*, 2–17; (i) Cohen, D. T.; Scheidt, K. A. *Chem. Sci.* **2012**, *3*, 53–57; (j) Bugaut, X.; Glorius, F. *Chem. Soc. Rev.* **2012**, *41*, 3511–3522.
4. (a) *N-Heterocyclic Carbenes in Synthesis*; Nolan, S. P., Ed.; Wiley-VCH: Weinheim, Germany, 2006; (b) Glorius, F. In *N-Heterocyclic Carbenes in Transition Metal Catalysis*; Springer: Berlin, 2007; (c) Herrmann, W. A. *Angew. Chem., Int. Ed.* **2002**, *41*, 1290–1309; (d) Peris, E.; Crabtree, R. H. *Coord. Chem. Rev.* **2004**, *248*, 2239–2246; (e) Díez-González, S.; Nolan, S. P. *Coord. Chem. Rev.* **2007**, *251*, 874–883; (f) Kantchev, E. A. B.; O'Brien, C. J.; Organ, M. G. *Angew. Chem., Int. Ed.* **2007**, *46*, 2768–2813; (g) Würtz, S.; Glorius, F. *Acc. Chem. Res.* **2008**, *41*, 1523–1533; (h) Díez-González, S.; Marion, N.; Nolan, S. P. *Chem. Rev.* **2009**, *109*, 3612–3676.
5. For other aspects, see: (a) Perry, M. C.; Burgess, K. *Tetrahedron: Asymmetry* **2003**, *14*, 951–961; (b) Cesar, V.; Bellemin-Laponnaz, S.; Gade, L. H. *Chem. Soc. Rev.* **2004**, *33*, 619–636; (c) Snead, D. R.; Seo, H.; Hong, S. *Curr. Org. Chem.* **2008**, *12*, 1370–1387; (d) Crudden, C. M.; Allen, D. P. *Coord. Chem. Rev.* **2004**, *248*, 2247–2273; (e) Scott, N. M.; Nolan, S. P. *Eur. J. Inorg. Chem.* **2005**, 1815–1828; (f) Marion, N.; Nolan, S. P. *Acc. Chem. Res.* **2008**, *41*, 1440–1449.
6. Würtz, S.; Lohre, C.; Fröhlich, R.; Bergander, K.; Glorius, F. *J. Am. Chem. Soc.* **2009**, *131*, 8344–8345.
7. (a) Glorius, F.; Altenhoff, G.; Goddard, R.; Lehmann, C. *Chem. Commun.* **2002**, 2704–2705; (b) Altenhoff, G.; Goddard, R.; Lehmann, C. W.; Glorius, F. *Angew. Chem., Int. Ed.* **2003**, *42*, 3690–3693; (c) Altenhoff, G.; Goddard, R.; Lehmann, C. W.; Glorius, F. *J. Am. Chem. Soc.* **2004**, *126*, 15195–15201; (d) Altenhoff, G.; Würtz, S.; Glorius, F. *Tetrahedron Lett.* **2006**, *47*, 2925–2928.
8. Grimme, S. *J. Chem. Phys.* **2006**, *124*, 034108–034116.
9. Tao, J.; Perdew, J. P.; Staroverov, V. N.; Scuseria, G. E. *Phys. Rev. Lett.* **2003**, *91*, 146401–146404.
10. Weigend, F.; Ahlrichs, R. *Phys. Chem. Chem. Phys.* **2005**, *7*, 3297–3305.
11. Grimme, S.; Antony, J.; Ehrlich, S.; Krieg, H. *J. Chem. Phys.* **2010**, *132*, 154104–154119.
12. Grimme, S.; Ehrlich, S.; Goerigk, L. *J. Comput. Chem.* **2011**, *32*, 1456–1465.
13. Ranganath, K. V. S.; Kloesges, J.; Schäfer, A. H.; Glorius, F. *Angew. Chem., Int. Ed.* **2010**, *49*, 7786–7789.
14. (a) Dorta, R.; Stevens, E. D.; Hoff, C. D.; Nolan, S. P. *J. Am. Chem. Soc.* **2003**, *125*, 10490–10491; (b) Hillier, A. C.; Sommer, W. J.; Yong, B. S.; Petersen, J. L.; Cavallo, L.; Nolan, S. P. *Organometallics* **2003**, *22*, 4322–4326; (c) Dorta, R.; Stevens, E. D.; Scott, N. M.; Costabile, C.; Cavallo, L.; Hoff, C. D.; Nolan, S. P. *J. Am. Chem. Soc.* **2005**, *127*, 2485–2495; (d) Cavallo, L.; Correa, A.; Costabile, C.; Jacobsen, H. *J. Organomet. Chem.* **2005**, *690*, 5407–5413; (e) Kelly, R. A., III; Clavier, H.; Giudice, S.; Scott, N. M.; Stevens, E. D.; Bordner, J.; Samardjiev, I.; Hoff, C. D.; Cavallo, L.; Nolan, S. P. *Organometallics* **2008**, *27*, 202–210; (f) Poater, A.; Cosenza, B.; Correa, A.; Giudice, S.; Ragone, F.; Scarano, V.; Cavallo, L. *Eur. J. Inorg. Chem.* **2009**, 1759–1766; (g) Clavier, H.; Nolan, S. P. *Chem. Commun.* **2010**, 841–861.
15. (a) Okamoto, S.; Tominaga, S.; Saino, N.; Kase, K.; Shimoda, K. *J. Organomet. Chem.* **2005**, *690*, 6001–6007; (b) Lavallo, V.; Canac, Y.; Präsang, C.; Donnadieu, B.; Bertrand, G. *Angew. Chem., Int. Ed.* **2005**, *44*, 5705–5709; (c) Lavallo, V.; Canac, Y.; De Hope, A.; Donnadieu, B.; Bertrand, G. *Angew. Chem., Int. Ed.* **2005**, *44*, 7236–7239; (d) Fructos, M. R.; Belderrain, T. R.; de Frémont, P.; Scott, N. M.; Nolan, S. P.; Díaz-Requejo, M. M.; Pérez, P. J. *Chem. Commun.* **2006**, 2045–2047; (e) Frey, G. D.; Lavallo, V.; Donnadieu, B.; Schoeller, W. W.; Bertrand, G. *Science* **2007**, *316*, 439–441; (f) Lavallo, V.; Frey, G.; Donnadieu, B.; Soleilhavoup, M.; Bertrand, G. *Angew. Chem., Int. Ed.* **2008**, *47*, 5224–5228; (g) Organ, M. G.; Calimsiz, S.; Sayah, M.; Hoi, K. H.; Lough, A. J. *Angew. Chem., Int. Ed.* **2009**, *48*, 2383–2387; (h) Schoeps, D.; Buhr, K.; Dijkstra, M.; Ebert, K.; Plenio, H. *Chem.—Eur. J.* **2009**, *15*, 2960–2965; (i) Berthon-Gelloz, G.; Siegler, M. A.; Spek, A. L.; Tinant, B.; Reek, J. N. H.; Markó, I. E. *Dalton Trans.* **2010**, *39*, 1444–1446; (j) Wu, L.; Drinkel, E.; Gaggia, F.; Capolicchio, S.; Linden, A.; Falivene, L.; Cavallo, L.; Dorta, R. *Chem.—Eur. J.* **2011**, *17*, 12886–12890.
16. Buried volumes were calculated using SambVca. Parameters used for SambVca calculations: 3.50 Å was selected as the value for the sphere radius, 2.00 Å was considered as distances for the metal–ligand bond and Bondi radii scaled by 1. 17 were used;https://www.molnac.unisa.it/OMtools/sambvca.php.
17. Simone, G.; Weber, S. G.; Loos, C.; Rominger, F.; Straub, B. F. *ARKIVOC* **2012**, 226–242.
18. (a) Díez-González, S.; Kaur, H.; Zinn, F. K.; Stevens, E. D.; Nolan, S. P. *J. Org. Chem.* **2005**, *70*, 4784–4796; (b) Iglesias, M.; Beetstra, D. J.; Knight, J. C.; Ooi, L.-L.; Stasch, A.; Coles, S.; Male, L.; Hursthouse, M. B.; Cavell, K. J.; Dervisi, A.; Fallis, I. A. *Organometallics* **2008**, *27*, 3279–3289; (c) Bo-Lin, L.; Peng, K.; Stack, T. D. P. *Organometallics* **2010**, *29*, 3683–3685.
19. Johansson, C. C. C.; Colacot, T. J. *Angew. Chem., Int. Ed.* **2010**, *49*, 676–707.
20. Lee, S.; Hartwig, J. F. *J. Org. Chem.* **2001**, *66*, 3402–3415.
21. For reviews, see: (a) Miura, M.; Nomura, M. *Top. Curr. Chem.* **2002**, *219*, 211–241; (b) Culkin, D. A.; Hartwig, J. F. *Acc. Chem. Res.* **2003**, *36*, 234–245.
22. (a) Kündig, E. P.; Seidel, T. M.; Jia, Y.-X.; Bernardinelli, G. *Angew. Chem., Int. Ed.* **2007**, *46*, 8484–8487; (b) Jia, Y.-X.; Hillgren, J. M.; Watson, E. L.; Marsden, S. P.; Kündig, E. P. *Chem. Commun.* **2008**, 4040–4042.
23. For further examples, see: (a) Bertogg, A.; Campanovo, F.; Togni, A. *Eur. J. Inorg. Chem.* **2005**, 347–356; (b) Luan, X.; Mariz, R.; Robert, C.; Gatti, M.; Blumentritt, S.; Linden, A.; Dorta, R. *Org. Lett.* **2008**, *10*, 5569–5572; (c) Durbin, M. J.; Willis, M. C. *Org. Lett.* **2008**, *10*, 1413–1415; (d) Luan, X.; Wu, L.; Drinkel, E.; Mariz, R.; Gatti, M.; Dorta, R. *Org. Lett.* **2010**, *12*, 1912–1915; (e) Wu, L.; Falivene, L.; Drinkel, E.; Grant, S.; Linden, A.; Cavallo, L.; Dorta, R. *Angew. Chem. Int. Ed.* **2012**, *51*, 2870–2873.
24. Jia, Y.-X.; Katayev, D.; Bernardinelli, G.; Seidel, T. M.; Kündig, E. P. *Chem.—Eur. J.* **2010**, *16*, 6300–6309.
25. For first reports, see: (a) Palucki, M.; Buchwald, S. L. *J. Am. Chem. Soc.* **1997**, *119*, 11108–11109; (b) Hamann, B. C.; Hartwig, J. F. *J. Am. Chem. Soc.* **1997**, *119*, 12382–12383; (c) Satoh, T.; Kawamura, Y.; Miura, M.; Nomura, M. *Angew. Chem., Int. Ed.* **1997**, *36*, 1740–1742.
26. Singh, R.; Nolan, S. P. *J. Organomet. Chem.* **2005**, *690*, 5832–5840.
27. Richter, C.; Ranganath, K. V. S.; Glorius, F. *Adv. Synth. Catal.* **2012**, *354*, 377–382.
28. The structure of **13** was confirmed by single-crystal X-ray analysis but the X-ray data were not good enough for publication.
29. (a) Viciu, M. S.; Germaneau, R. F.; Nolan, S. P. *Org. Lett.* **2002**, *4*, 4053–4056; (b) Viciu, M. S.; Navarro, O.; Germaneau, R. F.; Kelly, R. A.; Sommer, W.; Marion, N.; Stevens, E. D.; Cavallo, L.; Nolan, S. P. *Organometallics* **2004**, *23*, 1629–1635.
30. A development of University of Karlsruhe and Forschungszentrum Karlsruhe GmbH, 1989–2007, TURBOMOLE GmbH, since 2007; available fromTURBOMOLE V6.3; 2011 :; http://www.turbomole.com.
31. Eichkorn, K.; Weigend, F.; Treutler, O.; Ahlrichs, R. *Theor. Chem. Acc.* **1997**, *97*, 119–124.
32. Weigend, F. *Phys. Chem. Chem. Phys.* **2002**, *4*, 4285–4291.
33. Hättig, C.; Weigend, F. *J. Chem. Phys.* **2000**, *113*, 5154–5161.
34. Weigend, F.; Häser, M.; Patzelt, H.; Ahlrichs, R. *Chem. Phys. Lett.* **1998**, *294*, 143–152.
35. Kind, C.; Reiher, M.; Neugebauer, J.; Hess, B. A. *SNF Version 2.2.1*; University of Erlangen: 2002.