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Chiral PEPPSI Complexes: Synthesis, Characterization, and Application in Asymmetric Suzuki–Miyaura Coupling Reactions

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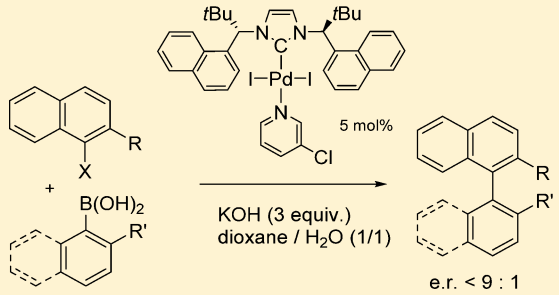
Supporting Information

ABSTRACT: PEPPSI complexes incorporating chiral N-heterocyclic carbene (NHC) ligands based on 2,2-dimethyl-1-(*o*-substituted aryl)-propan-1-amines were synthesized. Two complexes, with one saturated and one unsaturated NHC ligand, were structurally characterized. The chiral PEPPSI complexes were used in asymmetric Suzuki–Miyaura reactions, giving atropisomeric biaryl products in modest to good enantiomeric ratios.



INTRODUCTION

The synthesis of chiral biaryl compounds has received considerable attention, because this structural motif is present in many natural products and chiral ligands for transition-metal-catalyzed reactions.[1] Atroposelective C–C cross coupling via asymmetric palladium-catalyzed Suzuki–Miyaura reactions represents a powerful approach of access to this class of compounds.[2] To date, most of the protocols have employed chiral mono- or diphosphine ligands under homogeneous or heterogeneous conditions,[3,4] bishydrazone or phosphine–hydrazone chiral ligands,[5] chiral diene ligands,[6] or a pyridylmethylamine ligand with a stereogenic center.[7] The use of chiral N-heterocyclic carbene (NHC) ligands in asymmetric Suzuki–Miyaura coupling reactions is rare. Moreover, the reported reactions tend to lead to moderate asymmetric induction.[8]

Over the past few years, our group has developed bulky chiral NHC's derived from chiral *ortho*-substituted α-alkylphenethylamine (Figure 1). These ligands were successfully applied in the Pd-catalyzed intramolecular α-arylation of anilides to yield 3,3-disubstituted oxindoles in high yields and with excellent enantioselectivities.[9] More recently, palladium-catalyzed syntheses of highly enantioenriched 2,3-disubstituted and -fused indolines via C_{sp^3}–H/C(Ar) coupling reactions were reported.[10] This, and the first applications of these ligands in gold catalysis[11a] and the isolation of NHC–borane adducts,[11b] led us to explore the scope of such ligands in asymmetric palladium-catalyzed Suzuki–Miyaura coupling to access atropisomeric biaryls.

Achiral palladium–NHC complexes are well-known to be efficient in cross-coupling reactions and particularly for the coupling of *ortho* mono- and disubstituted aryl halides with hindered boronic acids.[12] The Pd^0–NHC active species is often generated in situ from air- and moisture-stable Pd^{II}–NHC complexes.[13] Many such precursors have been reported, including Pd^{II}–bis-NHC complexes,[14] donor-functionalized NHC–Pd^{II},[15] Pd^{II}–NHC–(η^3-allyl) precursors,[16,17] palladacycles,[18,19] and PEPPSI precatalysts.[20,21] PEPPSI complexes are obtained by direct palladation of an imidazolium salt in the presence of a weak base using 3-chloropyridine as solvent. The synthesis can be handled in the presence of air. The "user friendly" PEPPSI complexes efficiently catalyze the coupling of sterically demanding aryl halides with a variety of boronic acids at room temperature. Taking advantage of their convenience of access and handling, we herein report the synthesis of PEPPSI complexes incorporating chiral bulky N-heterocyclic carbenes and their application in asymmetric Suzuki–Miyaura coupling reactions.

RESULTS AND DISCUSSION

Synthesis of Chiral PEPPSI Complexes. Chiral PEPPSI complexes were obtained by following the procedure established by Organ and co-workers for achiral PEPPSI complexes.[20] Chiral imidazolium salts, $PdCl_2$ (1 equiv), and potassium carbonate (5 equiv) were stirred in 3-chloropyridine for 24 h. To avoid a mixture of halogen complexes, a halide exchange was performed by using an excess of NaI in CH_2Cl_2 at room temperature for 24 h. Workup (see the Experimental Section) afforded chiral PEPPSI complexes **10**–**14** in good yields (Scheme 1). These compounds are air and moisture stable and can be stored at room temperature for months without decomposition.

Chiral PEPPSI complexes with saturated NHC's were more difficult to synthesize than their unsaturated counterparts. Complex **14** was the only example that we were able to isolate. With dihydroimidazolium salts **6**–**8**, Pd(3-chloropyridine)$_2$I$_2$ formed instead.[22] It should be noted that PEPPSI complexes

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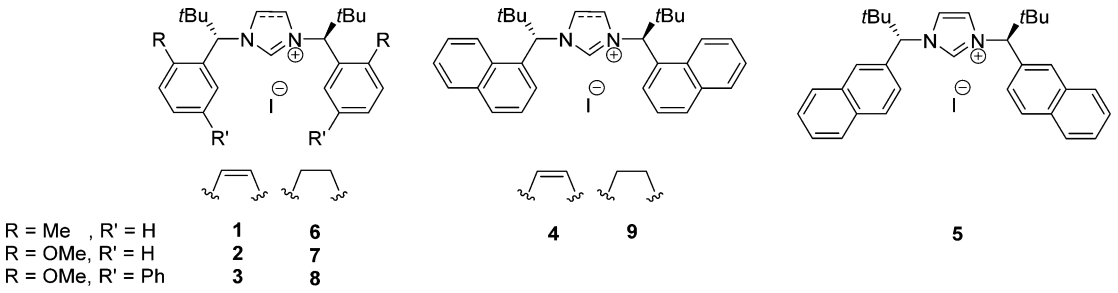
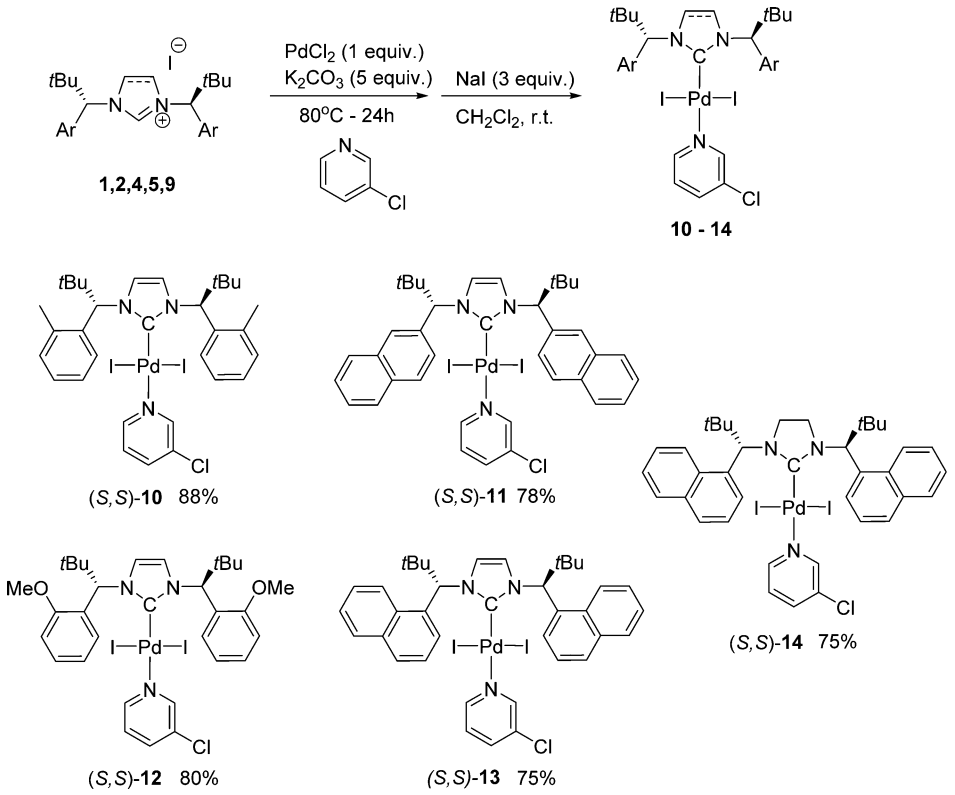


Figure 1. Chiral imidazolium and dihydroimidazolium ligand precursors.

Scheme 1. Synthesis of Chiral PEPPSI Complexes 10−14



with a saturated NHC are rare. Precedents include SIPr-PEPPSI (**15**),[23] the unsymmetrical PEPPSI complexes **16** with a chiral saturated NHC,[8c] and the complex **17** with triethylamine in place of pyridine as the labile ligand (Figure 2).[24]

It remains unclear why saturated-NHC PEPPSI complexes are more difficult to access than the unsaturated analogues. It is unlikely to be because of an impediment to generate in situ the saturated carbene by the action of a weak base in the presence of a Pd precursor, as this has already been described in a number of reports.[11a,23] We have been confronted with this problem also when trying to prepare NHC−borane adducts with a saturated NHC formed from the reaction of dihydroimidazolium salts with a strong base.[11b]

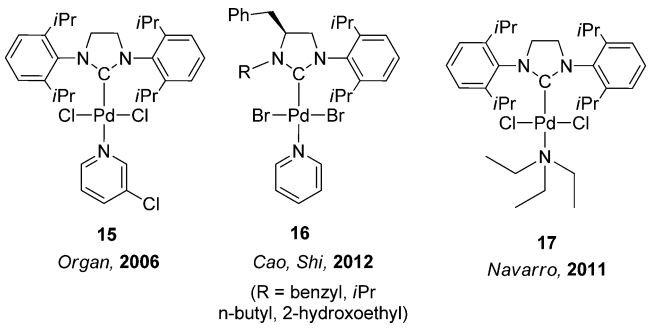


Figure 2. Achiral and chiral PEPPSI complexes (and an analogue) incorporating saturated NHC ligands.

NMR Studies. NHC generation and coordination was followed by ^{1}H NMR analysis by monitoring the disappearance of the imidazolium or dihydroimidazolium signal of C(2)−H and the appearance of the characteristic M−carbene carbon signal between 149.1 and 158.3 ppm in ^{13}C NMR for unsaturated NHC PEPPSI analogues **10−13** and a ^{13}C NMR signal at 187.9 ppm for complex **14** (Table 1). These values are consistent with literature data for Pd^{II}−NHC complexes and previously reported PEPPSI complexes.[23,25,26]

X-ray Crystallography. Yellow crystals suitable for X-ray analysis were obtained by slow diffusion of *n*-pentane into concentrated solutions of **13** and **14** in dichloromethane. Molecular structures are depicted in Figure 3, and select interatomic distances and bond angles are collected in Tables 2

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Table 1. Chemical Shift of the M−Carbene Carbon NCN in CD_2Cl_2 (101 MHz)

complex	δ_{NCN}(PEPPSI) (ppm)
10	149.1
11	152.0
12	158.3
13	152.3
14	187.9
IPr-PEPPSI[23]	153.5
16[8c]	182.1
17[16]	185.9

and 3. Compounds **13** and **14** both adopt square-planar geometries with a close to linear carbon−Pd−nitrogen array (Table 3). The Pd−NHC bonds for complexes **13** and **14** lie within the normal range of those observed for the achiral PEPPSI complexes that have been previously reported (IPr-PEPPSI, 1.969 (3) Å). Also, the Pd−I bond lengths are close to that reported for a PEPPSI analogue containing an iodide.[27] The Pd−N bonds again fall within the typical range for Pd−pyridine bonds in PEPPSI complexes (2.137 Å for IPr-PEPPSI[20] and 2.097 Å for IPent-PEPPSI).[28]

The main structural distortion by comparison with the achiral PEPPSI complexes reported by Organ and co-workers is that the pyridine lies nearly in the same plane as the N-heterocycle (torsion angle $N-C_{NHC}-Pd-N_{Py}-C \approx 17°$ for **13** and 19° in complex **14**), whereas for IPent-PEPPSI the pyridine is twisted out of the plane with a dihedral angle of 51°.[28] In Figure 4, IPent-PEPPSI and complexes **13** and **14** are represented by omitting the Pd−I bonds to see more clearly the relative position of the pyridine ring in relation to the plane of the N-heterocycle. As previously described by our group, the smallest subsituent (H) on the stereogenic centers of **13** and **14** is approximately coplanar with the Pd−NHC bond and the *o*-aryl substituent bond (in this case the second aromatic ring of the naphthyl moiety).[9−11] The stereogenic centers and the orientations of the aryl planes are set by the minimization of unfavorable allylic strain ($A_{1,3}$). Finally, we note that the molecular structures of complexes **13** and **14** are much alike. The main difference between the two complexes appears in the geometry of the N-heterocyclic core due to the saturation of the backbone in compound **14**. There is a slight difference in the N−C−N angles (106.3(3)° for **13** and 109.9(2)° for **14**), although it is within the range of what is usually observed in the literature.[28]

Table 2. Select Bond Lengths (Å) for Complexes 13 and 14

bond length	13	14
Pd−C	1.976(4)	1.977(2)
Pd−N	2.108(3)	2.115(2)
Pd−I1	2.6022(4)	2.5995(2)
Pd−I2	2.6027(4)	2.6088(3)
C−C	1.336(6)	1.509(4)

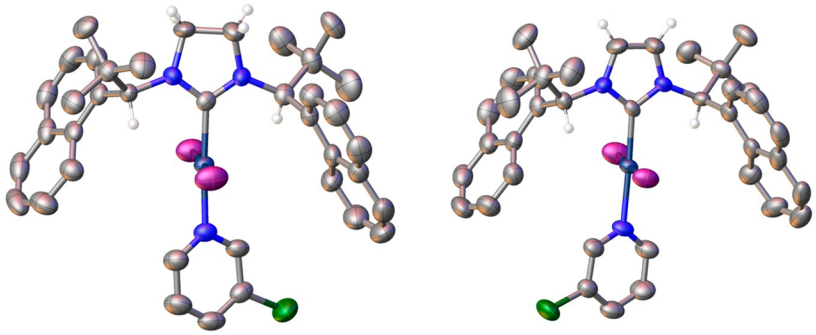
Table 3. Select Bond Angles (deg) for Complexes 13 and 14

bond angle	13	14
C−Pd−N	177.49(15)	176.66(10)
I1−Pd−I2	176.031(14)	176.214(10)
C−Pd−I2	90.96(7)	90.66(11)
N−C−N	106.3(3)	109.9(2)

On the basis of on their X-ray structures, the $\%V_{Bur}$ values of the chiral NHC ligands in **13** and **14** were determined using the Web application Samb*V*ca.[29] In Table 4 are presented the values obtained and comparison with the literature datas for IPent and IPr carbenes.[30] Appreciation of $\%V_{Bur}$ allowed us to classify our chiral ligands as sterically hindered NHCs with steric properties comparable to those of IPr for **13** and IPent for **14**.

Asymmetric Suzuki−Miyaura Coupling using Chiral PEPPSI Complexes. An initial screening revealed that complex **13** performed best in the asymmetric Suzuki−Miyaura coupling of 1-halo-2-substituted naphthalene with hindered boronic acids.[32] Optimization of the reaction conditions revealed a 1/1 mixture of dioxane/water associated with potassium hydroxide as base and 5 mol % of **13** to be an efficient combination for this reaction.[33]

The coupling of 1-bromo-2-methoxynaphthalene with a number of boronic acids was investigated (Table 5, entries 1−7). Using naphthylboronic acid as a coupling partner led to a high yield (90%) and moderate asymmetric induction (62% ee) (entry 1). Starting with 1.1 equiv of naphthylboronic acid instead of 1.5 equiv resulted in a significant decrease of activity but no degradation of enantioselectivity (entry 2). 1-Chloro-2-methoxynaphthalene (entry 3) gave a moderate yield at room temperature after 48 h. Coupling of 1-bromo-2-methoxynaphthalene with disubstituted boronic acids derived from naphthalene (entries 4 and 5) failed altogether, and no conversion was observed even at 40 °C, even though achiral bulky PEPPSI catalysts are known to be efficient catalysts to



(a) (b)

Figure 3. ORTEP representations of X-ray structures of (a) **14** and (b) **13**. All H atoms, except those at the stereogenic centers and on the N-heterocyclic core, are omitted for clarity.

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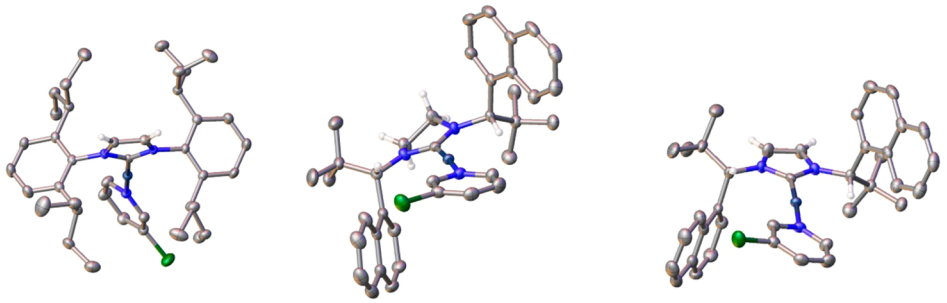


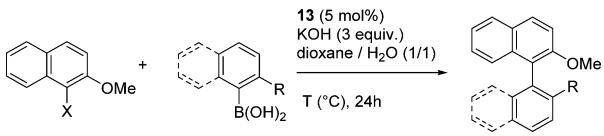
Figure 4. Comparison of the angles between pyridine and NHC planes.

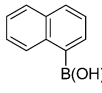
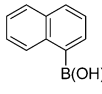
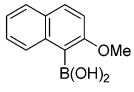
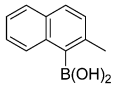
Table 4. Calculation of %V_{Bur} for Complexes 13 and 14[a]

complex	%V_{Bur}[31]
13	35.9
14	37.6
IPr PEPPSI	34.3
SIPr PEPPSI	39.3
IPent PEPPSI	37.9

[a]Pd–C bond fixed at 2.00 Å to compare with literature reports.[30]

Table 5. Asymmetric Suzuki–Miyaura Coupling of 1-Halo-2-methoxynaphthalene



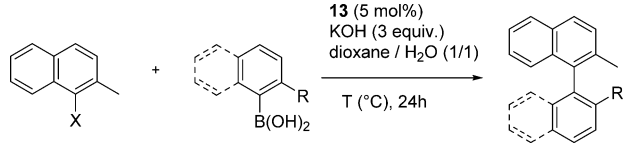
Entry	X	Ar-B(OH)$_2$	T(°C)	Yield (%)	e.r.
1	Br		25	90	81:19
2[a]	Br		25	26	82.5 : 17.5
3[b]	Cl		25	44	81.5 : 18.5
4[c]	Br		25 40	0 0	- -
5[c]	Br		25 40	0 0	- -
6	Br		25	72	79 : 21
7	Br		25	58	61.5 : 38.5

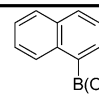
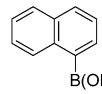
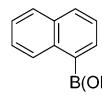
[a]1.1 equiv of naphthylboronic acid. [b]Reaction time 48 h. [c]Reaction time 72 h.

access tetrasubstituted biaryl products.[12] Using mono-*ortho*-substituted arylboronic acids afforded products in good to moderate yields (entries 6 and 7) but with low enantioselectivity (entry 7).

We anticipated that moving to an aryl halide with a bulkier substituent at the 2-position of the naphthalene would lead to higher selectivities. As such, the use of 1-bromo-2-methylnaphthalene was investigated (Table 6). The methyl group set close to the Ar–Ar′ bond generates more steric hindrance in the transition state in comparison to the previously used methoxy group. This hypothesis proved correct. Coupling of 1-halo-2-methylnaphthalene with naphthylboronic acid led to improved selectivities (77–80% ee) (entries 1 and 2). Under the previously optimized conditions (entry 1), 85% conversion was observed. However, a non-negligible amount of homocoupling product was generated during the process and was

Table 6. Asymmetric Suzuki–Miyaura Coupling of 1-Halo-2-methylnaphthalene



Entry	X	Ar-B(OH)$_2$	T(°C)	Yield (%)	e.r.
1	Br		25	85 (4/1)[a]	90 : 10
2	Br		25	42 (3/2)[a]	88.5 : 11.5
3[b]	Cl		25	67 (4/1)[a]	89 : 11
4	Br		25	87	78.5 : 21.5
5	Br		25 40	0 52	0 58 : 42

[a]Ratio product/1,1′-binaphthyl. [b]Reaction time 48 h.

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inseparable from the desired product. The ratio of byproduct in the final material was easily determined by ^{1}H NMR of the mixture by integration of the aromatic signal and was evaluated to be 4/1 (product/1,1′-binaphthyl). With *o*-tolylboronic acid we observed a loss of selectivity (57% ee) and the reaction required more time (72 h) to reach high yield (entries 4). Finally, with the bulky [1,1′-biphenyl]-2-ylboronic acid, no conversion was observed after 3 days at room temperature (entry 5). Increasing the temperature (24 h at 40 °C) allowed us to reach a moderate isolated yield but with a dramatic loss of enantioselectivity.

Atropisomeric 4-methyl-3-(2-methylnaphthyl)thiophene products are configurationally stable with a rotational barrier of ∼33.5 kcal/mol. Yamaguchi, Itami, and co-workers recently reported a palladium-catalyzed enantioselective C−H/C−B coupling of sterically hindered heteroarenes such as 3-methylthiophene with boronic acids in moderate yields and enantioselectivity.[34] When **13** was used as catalyst, the coupling reaction shown in Figure 5 gave the product in high isolated yield but with low selectivity (29% ee). Performing the reaction at lower temperature (15 °C) did not meet with success.[35]

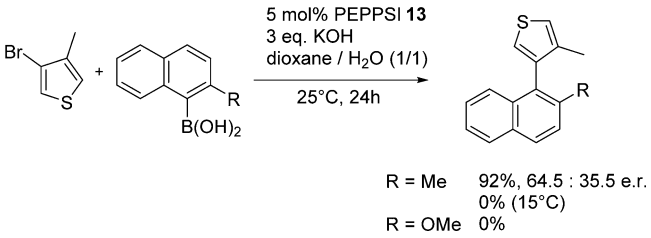

Figure 5. Asymmetric Suzuki−Miyaura coupling of 3-bromo-4-methylthiophene with boronic acids.

CONCLUSION

The synthesis and characterization of PEPPSI complexes incorporating chiral NHC ligands have been reported. Their application in asymmetric Suzuki−Miyaura coupling has shown good yields and moderate to good enantioselectivities. The results are highly dependent on the substrate used. Good selectivity (80% ee) was observed for coupling of 1-bromo-2-methylnaphthalene with naphthylboronic acid, although the results did not reach the levels of literature precedent for this reaction. This notwithstanding, the coupling reaction results reported here are to date the best using chiral NHC catalysts.

EXPERIMENTAL SECTION

General Methods. Solvents were purified by filtration on drying columns containing alumina. Dioxane was distilled over calcium hydride. Reactions and manipulations involving organometallic or moisture-sensitive compounds were carried out under nitrogen. Glassware was dried by heating under vacuum as necessary.

Starting Materials and Reagents. 3-Chloropyridine, 1-naphthylboronic acid, 3-bromo-4-methylthiophene, *o*-tolylboronic acid, 1-bromo-2-methylnaphthalene, and [1,1′-biphenyl]-2-ylboronic acid were purchased from Aldrich and used as received. KOH and anhydrous K_2CO_3 were stored in a desiccator. Chiral amines and chiral imidazolium and dihydroimidazolium salts were synthesized following literature procedures.[9,36] 1-Bromo-2-methoxynaphthalene[37] and 1-chloro-2-methoxynaphthalene were prepared as described previously.[38]

Characterizations. ^{1}H and ^{13}C{^{1}H} NMR spectra were recorded on Bruker AMX 400, 300, and 500 MHz spectrometers. Chemical shifts (δ) are reported in ppm compared to TMS using the residual peak of a deuterated solvent as internal standard. Coupling constants J are reported in Hz. Infrared spectra were recorded on a Perkin-Elmer Spectrum One spectrophotometer. Flash chromatography was carried out with silica gel 60 (40 μm). Analytical HPLC was performed using an Agilent 1100 series chromatograph with a JASCO PU-980 pump and Agilent 1100 Series detection system. GC analyses were performed on a HP6890 series apparatus with an injector, and helium was used as carrier gas.

General Procedure for the Synthesis of Chiral PEPPSI Complexes. A Schlenk tube was charged with $PdCl_2$ (1 equiv), NHC·HI (1.1 equiv), K_2CO_3 (5 equiv), and 3-chloropyridine (to give $C \approx 0.1-0.25$ mol/L). The mixture was stirred vigorously for 24 h at 80 °C. After it was cooled to room temperature, the reaction mixture was diluted with CH_2Cl_2 and passed through a short pad of Celite. NaI (∼5 equiv) and a stirring bar were added to the filtrate, and the solution was stirred for 24 h at room temperature. Filtration through a small pad of Celite, addition of CH_2Cl_2, and removal of excess 3-chloropyridine under reduced pressure afforded the PEPPSI complex.

(S,S)-10. The general procedure was applied starting from $PdCl_2$ (32 mg, 0.18 mmol), (*S*,*S*)-1,3-bis(2,2-dimethyl-1-*o*-methylphenylpropyl)imidazolium iodide (107 mg, 0.2 mmol), K_2CO_3 (126 mg, 0.9 mmol), and 3-chloropyridine (∼1 mL). For the anion exchange an excess of NaI (∼150 mg, 1 mmol) was used and the product was obtained as an orange solid (138 mg, 88%). Yellow crystals were obtained by slow diffusion of *n*-pentane into a concentrated solution of **10** in dichloromethane: $[\alpha]_D^{20} = -66.9°$ (c = 5.9 mg/mL, CH_2Cl_2); mp 115 °C; ^{1}H NMR (CD_2Cl_2, 400 MHz) δ 1.16 (s, 18H, $CH_{3\ tBu}$), 2.94 (s, 6H, $CH_{3\ ortho}$), 6.55 (s, 2H, NC*H*), 7.05−7.24 (m, 8H, CH_{Ar}), 7.31 (dd, J_{HH} = 8 Hz, J_{HH} = 5 Hz, 1H, CH_{Py}), 7.74 (s, 2H, $CH_{Im-4/5}$), 7.76−7.81 (m, 1H, CH_{Py}), 9.05 (d, J_{HH} = 2 Hz, 1H, $CH_{Py\text{-}ortho}$), 9.14 (d, J_{HH} = 2 Hz, 1H, $CH_{Py\text{-}ortho}$) ppm; ^{13}C{^{1}H} NMR (CD_2Cl_2, 101 MHz) δ 22.9 ($CH_{3\ ortho}$), 29.4 ($CH_{3\ tBu}$), 37.9 (C_{tBu}), 68.5 (CH_{tBu}), 121.5 ($CH_{Im-4/5}$), 125.1 (CH_{Py}), 125.6 (CH_{Ar}), 127.6 (CH_{Ar}), 129.5 (CH_{Ar}), 131.5 (CH_{Ar}), 132.5 (C_q), 136.4 (C_q), 138.2 (CH_{Py}), 149.1 (NCN), 153.1 ($CH_{Py\text{-}ortho}$), 153.9 ($CH_{Py\text{-}ortho}$) ppm; ESI-MS m/z (%) 493.5 [M − 2I − 2H − PyCl]$^+$; FT-IR (ATR) 2960, 2920, 2872, 1463, 1419, 1401, 1366, 1226, 1195, 1162, 1118, 1049, 1016, 905, 844, 795, 744, 719, 689 cm^{-1}. Anal. Calcd for $C_{32}H_{40}ClI_2N_3Pd{\cdot}0.5CH_2Cl_2$: C, 43.14; H, 4.57; N, 4.64. Found: C, 43.21; H, 4.46; N, 4.52.

(S,S)-11. The general procedure was applied starting from $PdCl_2$ (13 mg, 0.073 mmol), the β-naphthyl-unsaturated imidazolium salt (50 mg, 0.084 mmol), K_2CO_3 (60 mg, 0.43 mmol), and 3-chloropyridine (∼0.5 mL). For the anion exchange NaI (∼55 mg, 0.36 mmol) was used and the product was obtained as an orange solid (54 mg, 78%): $[\alpha]_D^{20} = -258.0°$ (c = 5.0 mg/mL, CH_2Cl_2); mp 165 °C; ^{1}H NMR (CD_2Cl_2, 400 MHz) δ 1.27 (s, 18H, $CH_{3\ tBu}$), 6.51 (s, 2H), 7.29 (dd, J_{HH} = 5 Hz, J_{HH} = 8 Hz, 1H, CH_{Py}), 7.39−7.61 (m, 7H, CH_{Ar}), 7.66−8.00 (m, 10H, 7CH_{Ar} + 2 $CH_{Im-4/5}$, 1CH_{Py}), 8.82 (dd, J_{HH} = 1 Hz, J_{HH} = 5 Hz, 1H, CH_{Py}), 8.91 (d, J_{HH} = 2 Hz, 1H, CH_{Py}) ppm; ^{13}C{^{1}H} NMR (CD_2Cl_2, 101 MHz) δ 29.2 ($CH_{3\ tBu}$), 36.4 (C_{tBu}), 74.8 (CH_{tBu}), 121.4 ($CH_{Im-4/5}$), 125.3 (CH_{Py}), 126.4 (CH_{Ar}), 126.6 (CH_{Ar}), 127.7 (CH_{Ar}), 128.1 (CH_{Ar}), 128.2 (CH_{Ar}), 128.5 (CH_{Ar}), 130.1 (CH_{Ar}), 132.6 (C_q), 133.3 (C_q), 133.4 (C_q), 135.5 (C_q), 138.2 (CH_{Py}), 152.0 (NCN), 152.5 (CH_{Py}), 153.3 (CH_{Py}) ppm; ESI-MS m/z (%) 565.3 [M − 2I − 2H − PyCl]$^+$; FT-IR (ATR) 3055, 2962, 2929, 2872, 1719, 1597, 1564, 1508, 1464, 1417, 1401, 1367, 1332, 1270, 1225, 1189, 1164, 1118, 1099, 1050, 1015, 959, 882, 853, 786, 763, 742, 688, 648, 625 cm^{-1}.

(S,S)-12. The general procedure was applied starting from $PdCl_2$ (14.7 mg, 0.083 mmol), the *o*-methoxy-unsaturated imidazolium salt (50 mg, 0.09 mmol), K_2CO_3 (62 mg, 0.45 mmol), and 3-chloropyridine (∼0.5 mL). For the anion exchange NaI (∼60 mg, 0.41 mmol) was used and the product was obtained as an orange solid (59 mg, 80%): $[\alpha]_D^{20} = -31.2°$ (c = 8.0 mg/mL, CH_2Cl_2); mp 207 °C; ^{1}H NMR (CD_2Cl_2, 400 MHz) δ 1.12 (s, 18H, $CH_{3\ tBu}$), 3.91 (s, 6H, OCH_3), 6.86−6.98 (m, 6H, NC*H* + CH_{Ar}), 7.12 (br s, 2H), 7.22−7.28 (m, 2H), 7.30 (dd, J_{HH} = 5 Hz, J_{HH} = 8 Hz, 1H, CH_{Py}), 7.66 (s, 2H, $CH_{Im-4/5}$), 7.75 (ddd, J_{HH} = 1 Hz, J_{HH} = 2 Hz, J_{HH} = 8 Hz, 1H, CH_{Py}), 8.89 (d, J_{HH} = 5 Hz, 1H, $CH_{ortho\text{-}Py}$), 9.05 (d, J_{HH} = 2 Hz, 1H,

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$CH_{ortho\text{-}Py}$) ppm; $^{13}C\{^1H\}$ NMR (CD_2Cl_2, 101 MHz) δ 29.2 ($CH_{3\ tBu}$), 37.2 (C_{tBu}), 55.8 (OCH_3), 112.0 (CH), 119.2 (CH), 120.1($CH_{Im\text{-}4/5}$), 124.9 (CH_{Py}), 128.8 (CH), 130.1 (CH), 137.9 (C_{Py}), 152.2 ($CH_{Py\text{-}ortho}$), 153.2 ($CH_{Py\text{-}ortho}$), 158.3 (NCN) ppm; ESI-MS m/z (%) 525.3 $[M - 2I - 2H - PyCl]^+$; FT-IR (ATR) 2953, 2923, 2855, 1728, 1601, 1589, 1565, 1492, 1460, 1422, 1403, 1368, 1332, 1288, 1243, 1198, 1185, 1164, 1108, 1051, 1031, 931, 908, 852, 842, 797, 778, 746, 729, 689, 627 cm^{-1}. Anal. Calcd for $C_{32}H_{40}ClI_2N_3O_2Pd$: C, 42.97; H, 4.51; N, 4.70. Found: C, 42.71; H, 4.41; N, 4.70.

*(R,R)-**13***. The general procedure was applied starting from $PdCl_2$ (10.1 mg, 0.056 mmol), the α-naphthyl-unsaturated imidazolium salt (39 mg, 0.066 mmol), K_2CO_3 (45 mg, 0.25 mmol), and 3-chloropyridine (~0.5 mL). For the anion exchange NaI (~40 mg, 0.28 mmol) was used and the product was obtained as an orange solid (40 mg, 75%). Yellow crystals were obtained by slow diffusion of *n*-pentane into a concentrated solution in dichloromethane: $[\alpha]_D^{20}$ = +183.6° (*c* = 5.8 mg/mL, CH_2Cl_2); mp >250 °C dec; ^1H NMR (CD_2Cl_2, 400 MHz) δ 1.20 (s, 18H, $CH_{3\ tBu}$), 6.99 (dd, J_{HH} = 8 Hz, J_{HH} = 5 Hz, 1H, CH_{Py}), 7.27 (s, 2H, CH_{tBu}), 7.30 (m, 2H, CH_{Ar}), 7.51 (m, 6H), 7.60 (ddd, J_{HH} = 1 Hz, J_{HH} = 2 Hz, J_{HH} = 8 Hz, 1H, CH_{Py}), 7.79 (dd, J_{HH} = 1 Hz, J_{HH} = 5 Hz, 1H, CH_{Py}), 7.86 (d, J_{HH} = 8 Hz, 2H, CH_{Ar}), 7.89 (s, 2H, $CH_{Im\text{-}4/5}$), 7.93–8.00 (m, 3H, $2CH_{Ar}$ + 1 CH_{Py}), 8.77 (d, J_{HH} = 8 Hz, 2H, CH_{Ar}) ppm; $^{13}C\{^1H\}$ NMR (CD_2Cl_2, 101 MHz) δ 29.6 ($CH_{3\ tBu}$), 37.5 (C_{tBu}), 67.9 (CH_{tBu}), 121.5 ($CH_{Im\text{-}4/5}$), 124.4 (CH_{Py}), 125.6 (CH_{Ar}), 125.8 (CH_{Ar}), 126.1 (CH_{Ar}), 126.7 (CH_{Ar}), 128.5 (CH_{Ar}), 128.8 (CH_{Ar}), 129.7 (CH_{Ar}), 131.8 (C_q), 134.6 (C_q), 134.8 (C_q), 135.4 (C_q), 137.9 (CH_{Py}), 152.3 (NCN), 153.0 (CH_{Py}), 153.7 (CH_{Py}) ppm; ESI-MS m/z (%) 565.3 $[M - 2I - 2H - PyCl]^+$; FT-IR (ATR) 3050, 2965, 2924, 2872, 1663, 1593, 1510, 1475, 1437, 1397, 1368, 1317, 1263, 1233, 1117, 1049, 950, 912, 870, 778, 745, 691, 645, 625 cm^{-1}. Anal. Calcd for $C_{38}H_{40}ClI_2N_3Pd\cdot 0.4CH_2Cl_2$: C, 47.63; H, 4.25; N, 4.34. Found: C, 47.73; H, 4.03; N, 4.38.

*(S,S)-**14***. The general procedure was applied starting from $PdCl_2$ (16 mg, 0.091 mmol), the α-naphthyl-saturated dihydroimidazolium salt (59 mg, 0.1 mmol), K_2CO_3 (70 mg, 0.5 mmol), and 3-chloropyridine (~0.5 mL). For the anion exchange NaI (~70 mg, 0.45 mmol) was used and the product was obtained as an orange solid (66 mg, 75%). Yellow crystals were obtained by slow diffusion of *n*-pentane into a concentrated solution in dichloromethane: $[\alpha]_D^{20}$ = −159.5° (*c* = 6.1 mg/mL, CH_2Cl_2); mp >250 °C dec; ^1H NMR (CD_2Cl_2, 400 MHz) δ 1.15 (s, 18H, $CH_{3\ tBu}$), 4.42 (ddd, J_{HH} = 3 Hz, J_{HH} = 8 Hz, J_{HH} = 12 Hz, 4H, $CH_{2\ Im\text{-}4/5}$), 6.84 (s, 2H, CH_{tBu}), 6.92 (dd, J_{HH} = 8 Hz, 1H, CH_{Py}), 7.31 (ddd, J_{HH} = 1 Hz, J_{HH} = 7 Hz, J_{HH} = 8 Hz, 2H, CH_{Ar}), 7.42–7.65 (m, 8H, 6 CH_{Ar} + 2 CH_{Py}), 7.80 (d, J_{HH} = 2 Hz, 1H, CH_{Py}), 7.88 (d, J_{HH} = 8 Hz, 2H, CH_{Ar}), 7.94 (d, J_{HH} = 8 Hz, 2H, CH_{Ar}), 8.69 (d, J_{HH} = 8 Hz, 2H, CH_{Ar}) ppm; $^{13}C\{^1H\}$ NMR (CD_2Cl_2, 101 MHz) δ 29.3 ($CH_{3\ tBu}$), 36.9 (C_{tBu}), 50.4 ($CH_{2\ Im\text{-}4/5}$), 65.4 (CH_{tBu}), 123.9 CH_{Py}), 125.4 (CH_{Ar}), 125.5 (CH_{Ar}), 126.3 (CH_{Ar}), 126.5 (CH_{Ar}), 127.4 (CH_{Ar}), 128.5 (CH_{Ar}), 129.5 (CH_{Ar}), 131.4 (C_q), 134.6 (C_q), 134.9 (C_q), 137.6 (CH_{Py}), 137.8 (C_q), 153.6 (CH_{Py}), 154.1 (CH_{Py}), 187.9 (NCN) ppm; ESI-MS m/z (%) 567.5 $[M - 2I - 2H - PyCl]^+$; FT-IR (ATR) 2955, 2924, 2872, 1722, 1663, 1593, 1563, 1510, 1475, 1437, 1397, 1368, 1317, 1263, 1233, 1117, 1049, 950, 912, 870, 778, 745, 691, 645, 625 cm^{-1}. Anal. Calcd for $C_{32}H_{42}ClI_2N_3Pd$: C, 48.74; H, 4.52; N, 4.49. Found: C, 48.40; H, 4.35; N, 4.31.

General Procedure for Asymmetric Suzuki–Miyaura Coupling with the Chiral PEPPSI Complex 13. A Radley carousel reactor tube was charged with the chiral PEPPSI complex **13** (0.005 mmol, 5 mol %), aryl halide (0.1 mmol), boronic acid (0.15 mmol), and KOH (3 equiv, 0.3 mmol). After three evacuation/N_2 fill cycles, 1,4-dioxane (1 mL) and water (1 mL) were added using a syringe and the solution was stirred for 24 h at the temperature indicated. Then water was added to the reaction mixture (1 mL) and the biphasic solution was extracted with Et_2O (3 × 2 mL). The organic layers were dried over Na_2SO_4 and filtered on cotton. Finally, the volatiles were removed under vacuum at room temperature. Depending on the final product, the residue obtained was purified by column chromatography on SiO_2 using pentane as eluent with different proportions of Et_2O (0–1%) or by PTLC with pentane (several elutions were sometimes required). Enantiomeric ratios were checked by chiral HPLC in 2-propanol or by SFC in Et_2O.

■ ASSOCIATED CONTENT

Supporting Information

Text, figures, a table, and CIF files giving experimental details and characterization data, ^1H NMR and $^{13}C\{^1H\}$ NMR spectra for products of catalysis, optimization of catalytic reactions, HPLC chromatograms, and X-ray data for **13** and **14**. This material is available free of charge via the Internet at http://pubs.acs.org. CCDC 957329 (for **14**) and 957330 (for **13**) also contain crystallographic data.

■ AUTHOR INFORMATION

Notes

The authors declare no competing financial interest.

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