Copper-Catalyzed Asymmetric Alkylation of Secondary Phosphines via Rapid Pyramidal Inversion in P–Stereogenic Cu–Phosphido Intermediates

Sarah K. Gallant, Ryan M. Tipker and David S. Glueck*

6128 Burke Laboratory, Department of Chemistry, Dartmouth College, Hanover, New Hampshire, 03755, United States

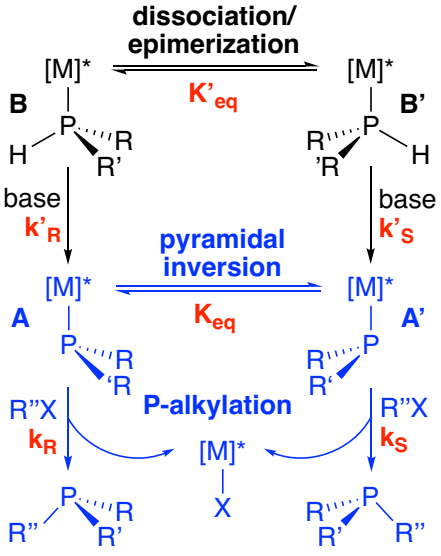
ABSTRACT: Development of metal-catalyzed asymmetric synthesis of P-stereogenic phosphines has been guided by the hypothesis that pyramidal inversion occurs rapidly in metal-phosphido intermediates, but this process has not been observed directly for all metals of interest. We report an enantioselective copper(Josiphos)-catalyzed alkylation of secondary phosphines and observation of the reaction intermediates, including variable temperature NMR studies of low-barrier pyramidal inversion at phosphorus in the key P-stereogenic terminal phosphido complexes Cu(diphos*)(PRR'), and investigation of their reversible formation from secondary phosphine-silanolate complexes Cu(diphos*)(PHR(R'))($OSiMe_3$).

INTRODUCTION

Metal-catalyzed enantioselective P–C bond formation via hydrophosphination of alkenes or phosphination of aryl or alkyl halides is a potentially useful way to prepare P-stereogenic phosphines, a privileged ligand class in asymmetric catalysis.[1] Scheme 1 (blue) summarizes the proposed mechanism for a typical process, catalytic asymmetric P-alkylation. In the key intermediates *L_nM–PRR', the metal promotes rapid pyramidal inversion of the phosphido group[2] and makes it nucleophilic,[3] while the chiral ligand controls the configuration at P and the relative reactivity of the two diastereomers.[4] The combination of a very fast equilibrium with a thermodynamic preference for one [M]*-phosphido diastereomer (K_{eq} = [**A'**]/[**A**]) and faster P-alkylation of one of them ($k_R > k_S$) results in enantioselectivity via Curtin-Hammett kinetics.[5]

Substitution-inert precious metals such as Pt, Pd, and Ru were initially used to ensure robust coordination of the chiral ligands, which might otherwise be displaced by the excess phosphine substrate and product.[6] Instead, cheaper earth-abundant metal catalysts are attractive targets, especially because their weaker M–P bonds should lead to faster ligand substitution.[7] We hypothesized that any metal can mediate rapid P-inversion, which is supported by experimental data for complexes of Ti, Zr, Hf, Nb, W, Mo, Re, Fe, Ru, Ni, Pd, Pt, and Ir, with d^0, d^2, d^4, d^6, and d^8 configurations.[8] NMR and computational studies of chiral Cu(I) phosphido complexes[7b,9] and the recent development of highly enantioselective Cu(Taniaphos)-catalyzed asymmetric P-alkylation[10] were also consistent with this idea, but inversion barriers in d^{10} metal-phosphido complexes had not been measured, and an unusually high computed barrier of 25 kcal/mol was reported for the model complex $CpZnPH_2$.[2] Even if P-inversion in Cu-phosphido catalytic intermediates was slower than P-alkylation, enantioselection could occur by the black route in Scheme 1. Because the diastereomeric Cu complexes **B** and **B'** interconvert rapidly by secondary phosphine dissociation, acid- or base-mediated epimerization, and re-coordination, a favorable equilibrium (K'_{eq}) and/or selective P-deprotonation ($k'_R > k'_S$) could result in enantioselection.[9]

Scheme 1. Proposed Mechanism of P–C Bond Formation and Origin of Enantioselectivity in Metal-Catalyzed Asymmetric Alkylation of P-Stereogenic Phosphines [a]



[a] [M]* = M(diphos*)(L_n), X = halide

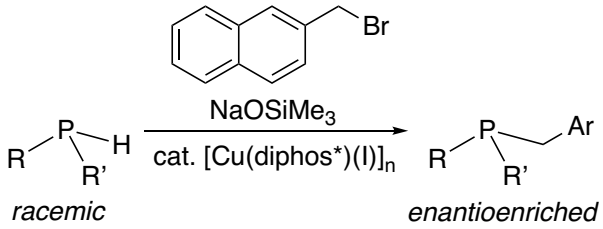
To address these general questions, we report mechanistic studies of Cu(diphos*)-catalyzed asymmetric P-alkylation, including direct observation of the hypothesized rapid inversion in phosphido

intermediates, as well as proton transfer equilibria involving copper-silanolate and -phosphido complexes.

RESULTS AND DISCUSSION

To investigate structure/reactivity/selectivity relationships in copper-catalyzed asymmetric P-alkylation, we screened the reaction of 2-bromomethylnaphthalene with a variety of P-stereogenic secondary phosphines PHR(R') using the precursors $[Cu(diphos^*)(I)]_n$ and the base $NaOSiMe_3$ (Scheme 2); see the Supporting Information for details.[11] The diarylphosphines PHPh(Ar) resulted in the cleanest and fastest conversions, often in minutes at 10 mol % catalyst loading, while alkylarylphosphines PHR(Ar) reacted more slowly, yielding byproducts. $NaOSiMe_3$ outperformed the stronger base $NaN(SiMe_3)_2$, which resulted in incomplete conversion and byproduct formation. Although enantioselectivity was low, these results demonstrated that copper-catalyzed asymmetric P-alkylation was possible.[12] Later, Yin and coworkers showed that a related Cu(Taniaphos) catalyst was highly selective.[10]

Scheme 2. Cu(diphos*)-Catalyzed Alkylation of Secondary Phosphines with 2-bromomethylnaphthalene [a]



[a] diphos* = (*R,R*)-Me-DuPhos, (*R,R*)-*i*-Pr-DuPhos, (*R,R*)-Me-FerroLANE, (*R,S*)-PPF-*t*-Bu, (*R,S*)-CyPF-*t*-Bu; PHRR' = PHMe(Is), PHMe(Mes), PHPh(Is), PHPh(*o*-An), PHPh(*t*-Bu), PHPh(Cy), PHMes(Men); Is = 2,4,6-(*i*-Pr)$_3$C$_6$H$_2$, Mes = 2,4,6-Me$_3$C$_6$H$_2$, *o*-An = *o*-C$_6$H$_4$OMe, Men = (–)-menthyl

Of the Josiphos and bis(phospholane) ligands screened, we chose (*R,S*)-PPF-*t*-Bu for further investigation of catalytic synthesis of P-stereogenic phosphines (Scheme 3, Table 1). These studies targeted preparation of bulky ligands bearing isityl (Is = 2,4,6-(*i*-Pr)$_3$C$_6$H$_2$) and supermesityl groups (Mes* = 2,4,6-(*t*-Bu)$_3$C$_6$H$_2$); the latter is little explored in the chemistry of chiral phosphines.[13] We also prepared P~N chelates[14] and PCP or PNP pincer precursors to test the hypothesis that N-coordination of 2-bromomethylpyridine or analogues to copper would promote P-alkylation by bringing the nucleophile and electrophile close together, as suggested in related couplings.[15] These approaches were partially successful. As observed in the screening experiments, diarylphosphine substrates reacted more quickly and selectively than the alkylarylphosphine PHMe(Is), which frequently yielded some of the byproduct diphosphine IsMeP–PMeIs as a mixture of diastereomers.[16] Although reactions were slower than analogous ones with P-Is substrates, the sterically demanding secondary phosphine PHPh(Mes*) was successfully alkylated (Table 1, entries 3 and 6-7). However, enantioselectivity for P-Is products **1**-**2** and diastereoselectivity in formation of Mes*-pincer precursors **6**-**7** was low. Similarly, although we could not determine the enantioselectivity of formation of the Mes*-phosphines **3** and **6**-**7**, comparison to samples prepared with achiral catalysts suggested that these reactions were also unselective (see the Experimental section and SI for details). Synthesis of P~N chelates **4**-**5** from 2-bromomethylpyridine was faster than analogous reactions with 2-bromomethylnaphthalene, but yields were reduced because the rate of decomposition of the pyridine substrate was competitive with the catalytic reaction.[17]

Scheme 3. Cu(PPF-*t*-Bu)-catalyzed alkylation of secondary phosphines and proposed intermediate with 2-bromomethylpyridine

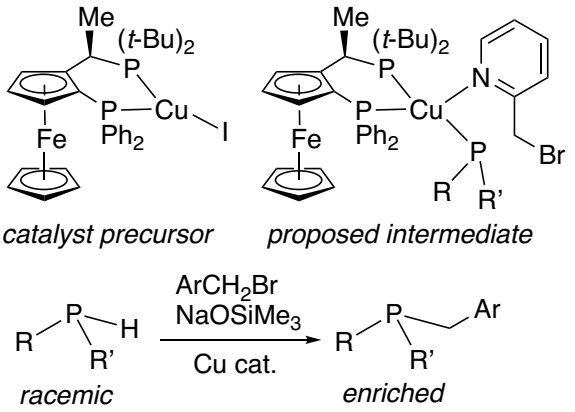
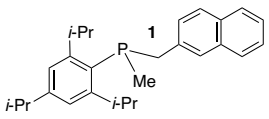
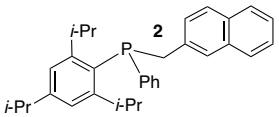
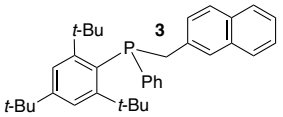
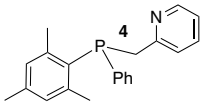
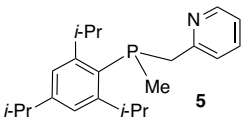
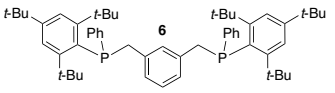
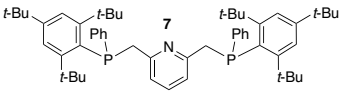


Table 1. Cu(PPF-*t*-Bu)-catalyzed alkylation of secondary phosphines [a]

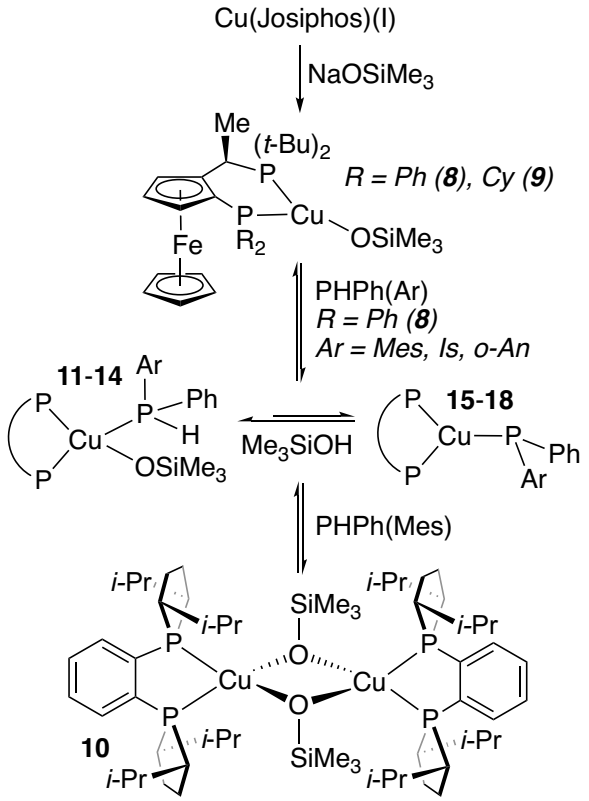
Entry	Product	Yield (%)	er [b]
1		92	64:36 [c]
2		89	56:44
3		84	nd
4		73	70:30
5 [d]		33	82:18
6		80	1.2:1 dr
7 [e]		78	1.3:1 dr

[a] 10 mol % catalyst loading; see the experimental section for details of the procedure, workup, and determination of enantiomeric ratio (er) and diastereomeric ratio (dr) [b] nd = not determined. See the experimental section for details; we were not able to determine the er of the P-Mes* derivatives. [c] When the reaction was done at –30 °C, the er was 77:23 [d]

The yield and er were determined with the product from separate catalytic runs [e] With the Cu(CyPF-*t*-Bu)(I) precursor, 91% yield, 1.4:1 dr

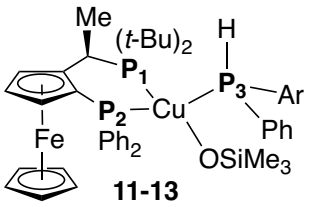
Mechanistic Studies To investigate the mechanisms of the catalytic reactions and the role of the proposed diastereomeric copper-phosphido intermediates, we studied stoichiometric reactions of the catalyst precursors with the substrates. Treatment of Cu(Josiphos)(I) with $NaOSiMe_3$ gave the silanolate complexes Cu(PPF-*t*-Bu)($OSiMe_3$) (**8**) and Cu(CyPF-*t*-Bu)($OSiMe_3$) (**9**), whose NMR spectra were similar to those of the Cu-I starting materials (Scheme 4). Addition of secondary phosphines to **8** or to [Cu(*R,R*)-*i*-Pr-DuPhos)($OSiMe_3$)]$_2$ (**10**)[9] generated mixtures containing the four-coordinate phosphine adducts **11-14**, in an apparent equilibrium with the three-coordinate Cu-phosphido complexes Cu(diphos*)(PRR') **15-18** and trimethylsilanol (Scheme 4). In some cases (see the experimental section), the free PPF-*t*-Bu or DuPhos ligands were observed in these mixtures, but the Cu-phosphine and -phosphido complexes were robust, persisting for days at room temperature. These diarylphosphido-Cu complexes were notably longer lived than analogous Cu(diphos*)(PMeIs) alkylarylphosphido complexes.[9]

Scheme 4. Synthesis of Cu(Josiphos) silanolate complexes **8-9**, and reaction of [Cu(diphos*)($OSiMe_3$)]$_n$ (**8** or **10** (ref 9)) with secondary diarylphosphines PHPh(Ar) to generate mixtures of phosphine adducts **11-14** and phosphido complexes **15-18** (diphos* = (*R,S*)-PPF-*t*-Bu, Ar = Mes (**11**, **15**), Is (**12**, **16**), *o*-An (**13**, **17**); diphos* = (*R,R*)-*i*-Pr-DuPhos, Ar = Mes (**14**, **18**))

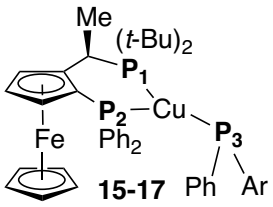


These mixtures were characterized by variable temperature $^{31}P\{^1H\}$ and ^{31}P NMR spectroscopy (Table 2). As in related Cu(diphos*) secondary phosphine complexes, one set of $^{31}P\{^1H\}$ NMR signals was observed at room temperature for **11**-**12** and **14**, consistent with rapid exchange on the NMR time scale between the two expected diastereomers.[9] The observation of P-P coupling between the inequivalent PPF-*t*-Bu donors in **11**-**12**, but only one $^{31}P\{^1H\}$ NMR signal in the secondary phosphine region, suggests that exchange between free and coordinated phosphine was rapid on the NMR time scale and was responsible for the interconversion of the diastereomers. At –75 °C, for PHPh(Is) complex **12**, two broad singlets were observed in the secondary phosphine region, consistent with slower exchange; the behavior of *i*-Pr-DuPhos complex **14** at room temperature was similar. In contrast, phenyl-*o*-anisylphosphine complex **13** gave rise to four PPF-*t*-Bu signals and two secondary phosphine resonances (three at –65 °C), consistent with slower exchange on the NMR time scale between four diastereomers, with a Cu-stereogenic center.

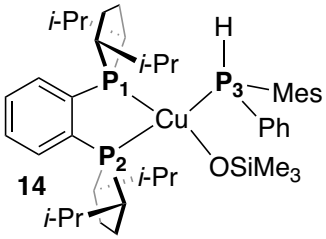
Table 2. $^{31}P\{^{1}H\}$ NMR Data for Cu(diphos*) Secondary Phosphine and Phosphido Complexes[a]



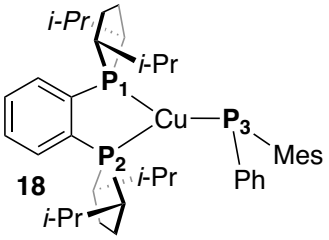
11-13



15-17



14



18

Complex	δ(diphos*)[b]	δ(P_3)	J_{12} (J_{13}, J_{23})	J_{PH}	dr
Cu((*R,S*)-PPF-*t*-Bu)($OSiMe_3$)(PHPh(Is)) (**11**)	31.0, –23.2	–83.2 [–81.5, –85.5][c]	161	218	2:1[c]
Cu((*R,S*)-PPF-*t*-Bu)($OSiMe_3$)(PHPh(Mes)) (**12**)	31.6, –23.6	–77.4	155	220	--
Cu((*R,S*)-PPF-*t*-Bu)($OSiMe_3$)(PHPh(*o*-An)) (**13a**) (**13b-c**) (**13d**)	53.5, –22.5 42.8–42.0, –15.4 to –15.9 39.4, –21.9	–53.8, –54.1	54 105	236, 237	d
Cu((*R,R*)-*i*-Pr-DuPhos)($OSiMe_3$)(PHPh(Mes)) (**14**)	–3.4	–76.5, –76.6	--	228, 229	1:1
Cu((*R,S*)-PPF-*t*-Bu)(PPhIs) (**15**)[e] (**15a**, major) (**15b**, minor)	41.3, –16.3 38.8, –15.7 36.7, –19.9	–55.2 –58.0 –63.1	113 (73, 54) 108 (80, 33) broad	--	5:1
Cu((*R,S*)-PPF-*t*-Bu)(PPhMes) (**16**)	40.7, –15.9	–42.3	114 (59, 48)	--	--
Cu((*R,S*)-PPF-*t*-Bu)(PPh(*o*-An)) (**17**)[f]	--	–57.1	(36)	--	--
Cu((*R,R*)-*i*-Pr-DuPhos)(PPhMes) (**18**)[g] (**18a**, minor) (**18b**, major)	4.6 2.9	–35.2 –33.9 –36.8	(65) (56) (57)	--	12:1

[a] 25 °C in THF or THF-d_8, unless indicated. The $^{31}P\{^{1}H\}$ NMR chemical shift standard was 85% H_3PO_4. Coupling constants are reported in Hz. [b] For PPF-*t*-Bu complexes, the P_1 signals ($P(t\text{-}Bu)_2$) are reported first, followed by the P_2 resonances (PPh_2). For *i*-Pr-DuPhos complexes, the formally inequivalent P_1 and P_2 nuclei had the same ^{31}P NMR chemical shifts, as in related complexes[9] [c] P_3 signals and dr reported at –75 °C. [d] Overlapping peaks at room and low temperature made determination of dr for the four diastereomers of complex **13** difficult. [e] dr and data for **15a-b** reported at –75 °C in THF. [f] –65 °C in THF; this complex was not observed at 25 °C, and only the phosphido signal (apparent t) could be identified [g] THF-d_8, dr, chemical shifts and coupling constants reported at –55 °C. The minor *i*-Pr-DuPhos signal was not observed

The secondary phosphine complexes **11-14** were observed in mixtures with phosphido complexes **15-18**, which were also characterized by $^{31}P\{^{1}H\}$ NMR spectroscopy (Table 2). As in related Cu-phosphido complexes,[9] P-P coupling to the diphos* ^{31}P nuclei was observed, with ABX spin systems for **15-17**, and an A_2B one with the more symmetrical DuPhos ligand in **18**. Two diastereomers of each complex are expected, but rapid P-phosphido inversion on the NMR time scale may result in observation of only one averaged set of signals, as seen for the PPF-*t*-Bu complexes **15**-**16** at 25 °C. In contrast, a mixture of phosphido complexes was seen even at room temperature for *i*-Pr-DuPhos complex **18**, with a 12:1 dr at –55 °C. The PPh(*o*-An) PPF-*t*-Bu phosphido complex **17** was not observed at room temperature, but on cooling to –55 °C, a low-intensity signal at –57.1 ppm (apparent t, J = 36 Hz) appeared.

At ambient temperature, the secondary phosphine complex/phosphido complex ratio depended on the ligands, as shown in Table 3, presumably due to changes in steric destabilization of the four-coordinate phosphine complexes and acidity of the coordinated phosphine.

Table 3. Ratios of the phosphine silanolate adducts Cu(diphos*)(PHPh(Ar))($OSiMe_3$) (**11-14**) to the phosphido complexes (Cu(diphos*)(PPh(Ar)) (**15-18**) observed by $^{31}P\{^{1}H\}$ NMR spectroscopy in THF at 25 °C

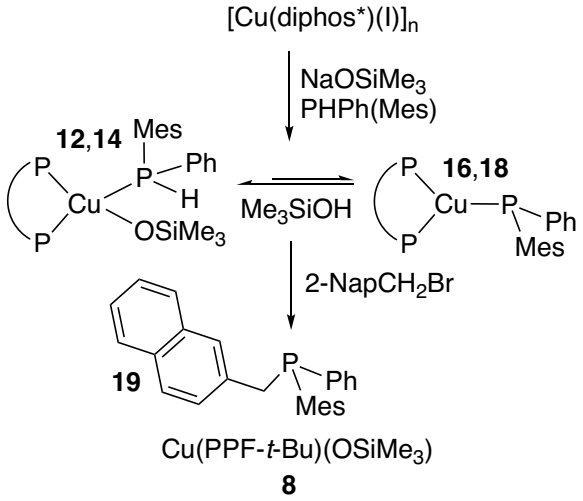
No.	Diphos*	phosphine	Ratio
11, 15	(*R,S*)-PPF-*t*-Bu	PHPh(Is)	3:1
12, 16	(*R,S*)-PPF-*t*-Bu	PHPh(Mes)	1.1:1
13, 17[a]	(*R,S*)-PPF-*t*-Bu	PHPh(*o*-An)	>20:1
14, 18	(*R,R*)-*i*-Pr-DuPhos	PHPh(Mes)	1.3:1

[a] –65 °C (phosphido complex **17** was not observed at 25 °C). Quantifying the ratio was challenging due to exchange of **13** with PHPh(*o*-An), but **17** was clearly a minor component (see the SI).

Dynamic processes in the mixture of **11** and **15** were investigated by low-temperature $^{31}P\{^{1}H\}$ NMR spectroscopy in THF. All three of the ^{31}P NMR signals for phosphido complex **15** coalesced around –55 °C, and at –75 °C, a 5:1 mixture of the expected two diastereomers was observed, with an ABX spin system for the major isomer and broad signals for the minor one (Table 2). The barrier to the dynamic process, which was presumably a combination of pyramidal inversion and rotation about the Cu–P bond, was 9 kcal/mol (see the SI for spectra and details),[18] consistent with a computed value of 12.8 kcal/mol for these combined processes in the model system $Cu(H_2PCH_2CH_2PH_2)(PH_2)$.[9]

To demonstrate that the Cu(diphos*)(PRR') phosphido complexes were catalytically competent intermediates, mixtures containing the phenylmesitylphosphido complexes **16** and **18** were generated and treated with 2-bromomethylnaphthalene to give tertiary phosphine **19** within 5 min, according to $^{31}P\{^{1}H\}$ NMR monitoring. With **16**, the main copper product was Cu((*R,S*)-PPF-*t*-Bu)($OSiMe_3$) (**8**), presumably by reaction of the initial Cu-Br product with excess $NaOSiMe_3$ (Scheme 5). The free ligands PPF-*t*-Bu and *i*-Pr-DuPhos, along with other unidentified byproducts, were also observed.

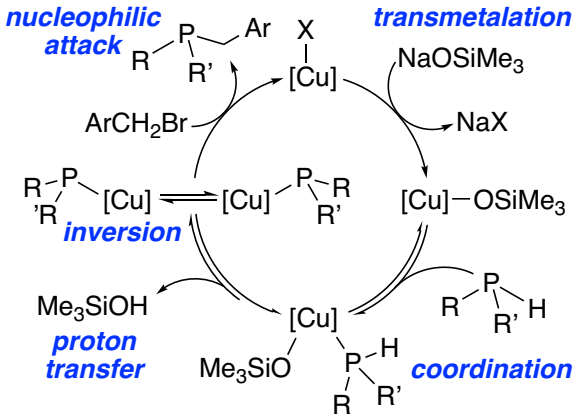
Scheme 5. Addition of 2-bromomethylnaphthalene to mixtures containing Cu(diphos*)(PPhMes) phosphido complexes **16** and **18** resulted in rapid P-benzylation to yield phosphine **19** (diphos* = (*R,S*)-PPF-*t*-Bu (**12** and **16**) or (*R,R*)-*i*-Pr-DuPhos (**14** and **18**))



CONCLUSIONS

These results provided fundamental information on the properties of rare copper terminal phosphido complexes and their role in catalysis. After developing copper-catalyzed asymmetric P-alkylation and applying it to some unusual bulky secondary phosphine substrates, we observed or isolated all of the intermediates in a proposed mechanism (Scheme 6). The active phosphido complexes were generated by intramolecular proton transfer in the phosphine-silanolate adducts Cu(diphos*)(PHPh(Ar))($OSiMe_3$), in equilibria whose positions depended on diphos* and P-Ar substituents. We confirmed the hypothesis that pyramidal inversion is fast in the chiral Cu(I) phosphido complexes Cu(diphos*)(PRR'), showing that d^{10} systems are similar to previously studied analogs with fewer d-electrons. Because phosphido complexes of several metals are nucleophilic and undergo rapid P-inversion, asymmetric synthesis of P-stereogenic phosphines does not require precious metals. We showed here that the substitution-labile Cu(I) forms active catalysts, and Yin's recent demonstration of high selectivity and broad substrate scope for the analogous Cu(Taniaphos) catalyst emphasizes the synthetic value of this approach.[10a] We expect that related catalysts using earth-abundant metals can be developed using these apparently general ideas.

Scheme 6. All the intermediates in the proposed mechanism of copper-catalyzed asymmetric P-alkylation were observed or isolated, including determination of the inversion barrier in a phosphido complex ([Cu] = Cu((*R,S*)-PPF-*t*-Bu), X = halide)



EXPERIMENTAL SECTION

General Experimental Details Unless otherwise noted, all reactions and manipulations were performed in dry glassware under a nitrogen atmosphere at ambient temperature in a glove box or using standard Schlenk techniques. Pentane, CH_2Cl_2, ether, THF, and toluene were dried over alumina columns similar to those described by Grubbs.[19] NMR spectra were recorded with 500 or 600 MHz spectrometers. ^{1}H or ^{13}C NMR chemical shifts are reported vs Me_4Si and were determined by reference to the residual ^{1}H or ^{13}C solvent peaks. ^{31}P NMR chemical shifts are reported vs H_3PO_4 (85%) used as an external reference. Coupling constants are reported in Hz, as absolute values. Unless indicated, peaks in NMR spectra are singlets. Atlantic Microlab (Norcross, GA) provided elemental analyses. Mass spectrometry was performed at the University of Illinois. Reagents were from commercial suppliers. The phosphines PHMe(Is), PHPh(Is) and PHPh(Mes*),[20] PHPh(Mes),[6a] and PHPh(*o*-An),[21] the Pd-chiral amine complex (*S*)-$\{Pd[NMe_2CH(Me)C_6H_4](Cl)\}_2$,[22] and the catalyst precursors $[Cu(diphos*)(I)]_n$[11] and Pt(dppe)(Me)(Cl)[23] were prepared by literature methods.

General Procedure for Copper-Catalyzed Phosphine Alkylation with 2-bromomethylnaphthalene To the catalyst precursor (10 mol %, 1 equiv) was added a solution of secondary phosphine (10 equiv) and 2-bromomethylnaphthalene (10.5 equiv) in 1 mL of THF. The solution was added to solid $NaOSiMe_3$ (11 equiv) and the resulting solution was stirred for 5 min-4 h, depending on the secondary phosphine. The reaction was monitored by $^{31}P\{^{1}H\}$ NMR spectroscopy. As the reaction progressed, a white solid formed. The solvent was removed under vacuum and the residue was extracted

with a 9:1 pentane/THF mixture. The resulting solution was passed through a silica column (10 cm height, 1 cm diameter), using 9:1 pentane/THF as eluent to give a colorless solution. The solvent was removed in vacuo, and the yield of a colorless oil was determined. A solution of (*S*)-{Pd[$NMe_2CH(Me)C_6H_4$](Cl)}$_2$ (~1.6 equiv Pd per phosphine) in 1 mL of benzene was added, and the er was determined via integration of product diastereomer peaks in the $^{31}P\{^1H\}$ NMR spectrum.[24] For example, with the catalyst precursor Cu((*R,S*)-PPF-*t*-Bu)(I), PHMe(Is) (18 mg, 0.072 mmol) gave 92% yield after 2 h (64:36 er), and PHPh(Is) (22 mg, 0.070 mmol) gave 89% yield after 5 min (56:44 er).

Copper-Catalyzed Phosphine Alkylation with 2-Bromomethylnaphthalene at –30 °C Solutions of the catalyst precursor Cu((*R,S*)-PPF-*t*-Bu)(I) (13 mg, 0.018 mmol, 18 mol %) and PHMe(Is) (25 mg, 0.10 mmol, 5.6 equiv) in 1 mL of THF and of 2-bromomethylnaphthalene (30 mg, 0.14 mmol, 7.8 equiv) and NaOSiMe$_3$ (20 mg, 0.18 mmol, 10 equiv) in 1 mL of THF were cooled to –30 °C in a freezer. After 30 min, the solutions were combined and the resulting orange solution was left in the freezer for 48 h. The reaction completion was determined by $^{31}P\{^1H\}$ NMR spectroscopy. After workup as in the general procedure to give 33 mg of product (85% yield), a solution of (*S*)-{Pd[$NMe_2CH(Me)C_6H_4$](Cl)}$_2$ (30 mg, 0.051 mmol, 1.2 equiv of Pd per phosphine) in 1 mL of benzene was added, and the er was determined via integration of product diastereomer peaks in the $^{31}P\{^1H\}$ NMR spectrum (C_6H_6): δ 14.5 (b), 13.7 (a), a/b = 77:23.

General Procedure for Copper-Catalyzed Phosphine Alkylation with 2-Bromomethylpyridine Hydrobromide To the catalyst precursor (10 mol %, 1 equiv) was added a solution of secondary phosphine (10.1 equiv) and 2-bromomethylpyridine hydrobromide (10 equiv) in 1 mL of THF. The solution was added to solid NaOSiMe$_3$ (22 equiv) and the resulting solution was stirred for 5 min-4 h, depending on the secondary phosphine. The reaction was monitored by $^{31}P\{^1H\}$ NMR spectroscopy. As the reaction progressed, a white solid formed. The solvent was removed under vacuum and the residue was extracted with a 9:1 pentane/THF mixture (2:1, 5:1, 6:1, and 8:1 pentane/THF mixtures were also used for the extraction; higher polarity increased the yield of product, but resulted in inferior separation from byproducts). The resulting solution was passed through a silica column (10 cm height, 1 cm diameter), using 9:1 pentane/THF as eluent to give a colorless solution. *P*-toluenesulfonic acid monohydrate (~1.4 equiv) was added to the product to protonate the pyridine, and the solvent was removed in vacuo. A solution of (*S*)-{Pd[$NMe_2CH(Me)C_6H_4$](Cl)}$_2$ (~1.6 equiv Pd per phosphine) in 1 mL of benzene was added, and the er was determined via integration of product diastereomer peaks in the $^{31}P\{^1H\}$ NMR spectrum. These reactions were typically run using 10-20 mg of the secondary phosphine. Note: perhaps because of Pd-pyridine coordination, the standard assay for enantioenrichment of these phosphines using a chiral Pd-amine complex gave complicated results.[24] To avoid this problem, we protonated the pyridine before treatment with the Pd complex.

PPhMes*(CH_2-2-naphthyl) (3) To the catalyst precursor, CuI (Puratronic grade, 99.998%, 1.3 mg, 0.0070 mmol, 10 mol %) was added a solution of Mes*PH(Ph) (25 mg, 0.070 mmol, 10 equiv) and 2-bromomethylnaphthalene (16 mg, 0.074 mmol, 10.5 equiv) in 1 mL of THF. The solution was added to solid NaOSiMe$_3$ (9.0 mg, 0.077 mmol, 11 equiv). The resulting orange solution was stirred for 24 h, and a white solid formed. The solvent was removed under vacuum to give an orange solid and the residue was extracted with a 9:1 pentane/THF mixture (3 mL). The resulting orange solution was passed through a silica column (10 cm height, 1 cm diameter), using 9:1 pentane/THF as eluent (10 mL) to give a colorless solution. The solvent was removed in vacuo to give 31 mg (93% yield) of a colorless oil. A similar procedure on the same scale with the catalyst precursor Cu((*R,S*)-PPF-*t*-Bu)(I) (5.0 mg, 0.0070 mmol, 10 mol %) gave 29 mg (84% yield).

HRMS m/z calcd for $C_{35}H_{44}P$ (MH^+): 495.3181. Found: m/z 495.3175. Anal. Calcd for $C_{35}H_{43}P$: C, 84.98; H, 8.76. Found: C, 82.37, H, 8.88. These results were consistent with oxidation of the air-sensitive phosphine: Anal. Calcd for $C_{35}H_{43}PO$: C, 82.32; H, 8.49. $^{31}P\{^1H\}$ NMR (CD_2Cl_2): δ –13.5. ^1H NMR (CD_2Cl_2): δ 7.78 (m, 1H, Ar), 7.70 (m, 2H, Ar), 7.54 (br, 1H, Ar), 7.50 (d, J = 2, 2H, Ar), 7.42 (m, 2H, Ar), 7.29 (d, J = 8, 1H, Ar), 7.18 (m, 2H, Ar), 7.10 (m, 3H, Ar), 3.70 (br ABX pattern, J_{AB} = 15, 2H CH_2), 1.39 (18H, *o*-*t*-Bu), 1.37 (9H, *p*-*t*-Bu). $^{13}C\{^1H\}$ NMR (CD_2Cl_2): δ 158.8 (d, J = 12, quat *o*-Mes*), 150.7 (quat *p*-Mes*), 144.5 (d, J = 30, quat ipso Ar), 137.5 (d, J = 20, quat ipso Ar), 133.5 (quat Ar), 131.8 (d, J = 2, quat Ar), 130.2 (d, J = 41, quat ipso Ar), 129.4 (Ar), 129.3 (Ar), 128.0 (d, J = 7, Ar), 127.7 (d, J = 2, Ar), 127.6, 127.4 (d, J = 9, Ar), 127.1 (d, J = 10, Ar), 125.7, 125.6 (d, J = 2, Ar), 125.1, 123.8 (d, J = 7, Ar), 39.4 (d, J = 4, quat *C*Me$_3$), 37.8 (quat *C*Me$_3$), 37.2 (d, J = 28, P-CH_2), 33.9 (d, J = 7, C*Me*$_3$), 30.9 (C*Me*$_3$).

Attempts to measure the enantiomeric enrichment of this phosphine by coordination to a chiral Pd-amine complex were unsuccessful, because binding appeared to be reversible. However, the $^{31}P\{^1H\}$ NMR spectrum of the mixture with Pd using racemic phosphine (prepared with CuI catalyst precursor) was identical to that of the mixture prepared with a chiral Cu catalyst, suggesting that the latter process was not enantioselective. PPhMes*(CH_2-2-naphthyl) (31.2 mg, 0.063 mmol, 1 equiv) was added to a solution of (*S*)-{Pd[$NMe_2CH(Me)C_6H_4$](Cl)}$_2$ (30 mg, 0.051 mmol, 1.6 equiv per phosphine) in C_6D_6 (1 mL). $^{31}P\{^1H\}$ NMR (C_6D_6, racemic phosphine): δ 48.7 (Pd complex), 46.5 (Pd complex), –13.7 (phosphine), ratio = 0.19/1.0/0.58. For a sample of phosphine (29 mg, 0.058 mmol, 1 equiv) prepared using the Cu((*R,S*)-PPF-*t*-Bu)(I) catalyst precursor and the Pd complex (30 mg, 0.051 mmol, 1.7 equiv per phosphine), the same $^{31}P\{^1H\}$ NMR signals were observed in C_6D_6, ratio = 0.19/1.0/0.65. After addition of another 1.6 equiv of the Pd complex to the racemic phosphine/Pd mixture, the ratio changed to 0.20/1.0/0.44, consistent with an equilibrium between free and coordinated phosphine.

PPhMes(CH_2-*o*-pyridyl) (4) For comparison to enantioenriched samples prepared via Cu-catalyzed reactions, we made racemic materials with an achiral platinum catalyst precursor. To Pt(dppe)(Me)(Cl) (5 mg, 0.008 mmol) was added a solution of PHPh(Mes) (18 mg, 0.08 mmol) in 1 mL of THF, followed by a solution of 2-bromomethylpyridine hydrobromide (21 mg, 0.084 mmol) and NaOSiMe$_3$ (20 mg, 0.18 mmol, 2.2 equiv) in 1 mL of THF. The solution was stirred overnight. The reaction progress was monitored by $^{31}P\{^1H\}$ NMR spectroscopy. As the reaction progressed, a white solid formed. The solvent was removed under vacuum and the residue was extracted with a 9:1 pentane/THF mixture. The resulting solution was passed through a silica column (10 cm

height, 1 cm diameter), using 9:1 pentane/THF as eluent to give a colorless solution. The solvent was removed under vacuum, resulting in a colorless oil (16 mg, 65%). This material contained an unidentified impurity, ($^{31}P\{^{1}H\}$ NMR δ 24.8, ~17% by NMR integration).

$^{31}P\{^{1}H\}$ NMR (C_6D_6): δ –20.0. ^{1}H NMR (C_6D_6): δ 8.42 (br d, J = 5, 1H, Ar), 7.50-7.47 (m, 2H, Ar), 7.09-7.06 (m, 2H, Ar), 7.00-6.95 (m, 2H, Ar), 6.88-6.87 (m, 1H, Ar), 6.72 (2H, Ar), 6.53-6.51 (m, 1H, Ar), 4.00 (ABX, dd, J = 2, 13, 1H, CH_2), 3.62 (ABX, dd, J = 3, 13, 1H, CH_2), 2.37 (6H, *o*-Me), 2.05 (3H, *p*-Me). $^{13}C\{^{1}H\}$ NMR (C_6D_6): δ 160.2 (d, J = 16, quat), 149.7 (Ar CH), 145.6 (d, J = 18, quat), 142.6 (d, J = 18, quat), 139.7 (quat), 135.8 (Ar CH), 130.8 (d, J = 20, quat), 130.1 (d, J = 4, Ar CH), 129.8 (d, J = 15, Ar CH), 128.7 (d, J = 3, Ar CH), 126.7 (Ar CH), 123.4 (d, J = 7, Ar CH), 120.8 (br d, Ar CH), 37.2 (d, J = 20, CH_2), 23.6 (d, J = 18, *o*-Me), 21.0 (*p*-Me).

Addition of D(+)-10-Camphorsulfonic Acid to PPhMes(CH$_2$-*o*-pyridyl) (4) for Confirmation of er Assay (A) To half of a clear oil of **4** (18 mg, 73%) separated from the reaction mixture as described in the general procedure was added D(+)-10-camphorsulfonic acid (8 mg, 0.03 mmol, 1.2 equiv) in 1 mL of CH_2Cl_2. (B) The other half of the oil was treated with HOTs and a solution of (*S*)-{Pd[$NMe_2CH(Me)C_6H_4$](Cl)}$_2$ as described above. $^{31}P\{^{1}H\}$ NMR integration of the spectrum of solution A gave er of 68:32 (δ –12.3 (minor), –12.6 (major)), while integration for B gave er of 71:29 (δ 30.6 (major), 18.4 (minor)), which are within error of each other. Note: camphorsulfonic acid has been used previously to protonate pyridines and determine enantioenrichment via NMR spectroscopy.[25]

PMe(Is)(CH$_2$-*o*-pyridyl) (5) To Pt(dppe)(Me)(Cl) (5 mg, 0.008 mmol) was added a solution of PHMe(Is) (20 mg, 0.08 mmol) in 1 mL of THF, followed by a solution of 2-bromomethylpyridine hydrobromide (30 mg, 0.084 mmol) and $NaOSiMe_3$ (30 mg, 0.18 mmol, 2.2 equiv) in 1 mL of THF. The mixture was stirred overnight. The reaction progress was monitored by $^{31}P\{^{1}H\}$ NMR spectroscopy. As the reaction progressed, a white solid formed. The solvent was removed under vacuum and the residue was extracted with a 9:1 pentane/THF mixture. The resulting solution was passed through a silica column (10 cm height, 1 cm diameter), using 9:1 pentane/THF as eluent to give a colorless solution. The solvent was removed under vacuum, resulting in a colorless oil (9.1 mg, 34%).

$^{31}P\{^{1}H\}$ NMR (C_6D_6): δ –42.1. ^{1}H NMR (C_6D_6): δ 8.42 (br d, J = 4, 1H, Ar), 7.14 (d, J = 2, 2H, Ar), 7.00 (overlapping dd, J = 2, 8, 1H, Ar), 6.93-6.92 (br m, 1H, Ar), 6.57-6.55 (br m, 1H, Ar), 4.23 (septet, J = 7, 2H, *o*-*i*-Pr CH), 3.69 (ABX, d, J = 13, 1H, CH_2), 3.41 (ABX, dd, J = 13, 1, 1H, CH_2), 2.76 (septet, J = 7, 1H, *p*-*i*-Pr CH), 1.57 (d, J = 7, 3H, P-Me), 1.34 (d, J = 7, 6H, *i*-Pr Me), 1.25 (d, J = 7, 6H, *i*-Pr Me), 1.97 (d, J = 7, 6H, *i*-Pr Me). $^{13}C\{^{1}H\}$ NMR (C_6D_6): δ 160.8 (d, J = 11, quat), 155.9 (d, J = 13, quat), 150.6 (quat), 149.7 (CH), 135.8 (Ar CH), 131.1 (d, J = 25, quat), 123.2 (d, J = 6, Ar CH), 122.3 (d, J = 4, Ar CH), 120.7 (d, J = 3, Ar CH), 39.5 (d, J = 20, CH_2), 34.7 (*i*-Pr CH), 31.6 (d, J = 22, *i*-Pr CH), 25.2 (*i*-Pr Me), 25.0 (*i*-Pr Me), 24.1 (*i*-Pr Me), 11.9 (d, J = 20, P-Me). For assay of the enantiopurity in Cu-catalyzed reactions, after adding HOTs and the chiral Pd complex described in the general procedure, $^{31}P\{^{1}H\}$ NMR signals were observed at δ 7.7 (major peak with Cu((*R*,*S*)-PPF-*t*-Bu)(I) precursor) and 6.5.

PCP Pincer Precursor 1,3-(PPhMes*CH$_2$)$_2$C$_6$H$_4$ (6) To the catalyst precursor (0.007 mmol, 10 mol % (1.3 mg of CuI, or 5.0 mg of Cu((*R*,*S*)-PPF-*t*-Bu-I)) was added a solution of Mes*PH(Ph) (22.3 mg, 0.0735 mmol, 10.5 equiv) and bis(2,6-dibromomethyl)benzene (9.3 mg, 0.035 mmol, 5.0 equiv) in 1 mL of THF. The solution was added to solid $NaOSiMe_3$ (9.0 mg, 0.077 mmol, 11 equiv). The resulting orange solution was stirred for 72 h, and a white solid formed. The reaction was monitored by $^{31}P\{^{1}H\}$ NMR spectroscopy every 24 h until only a trace of secondary phosphine remained. The solvent was removed under vacuum to give an orange solid and the residue was extracted with a 9:1 pentane/THF mixture (3 mL). The resulting orange solution was passed through a silica column (10 cm height, 1 cm diameter), using 9:1 pentane/THF as eluent (10 mL) to give a colorless solution. The solvent was removed in vacuo to yield a colorless oil (with CuI, 28 mg (99%); with Cu((*R*,*S*)-PPF-*t*-Bu)(I), 23 mg (80%)). This material contained a small amount of the secondary phosphine starting material (~1%, from $^{31}P\{^{1}H\}$ NMR integration).

HRMS m/z calcd for $C_{56}H_{77}P_2$ (MH^+): 811.5501. Found: m/z 811.5494. Anal. Calcd for $C_{56}H_{76}P_2$: C, 82.92; H, 9.44. Found: C, 79.05, H, 9.26. These results were consistent with oxidation of the air-sensitive phosphine, although the C analysis deviated from the expected value for the bis(phosphine dioxide): Anal. Calcd for $C_{56}H_{76}P_2O_2$: C, 79.77; H, 9.09. $^{31}P\{^{1}H\}$ NMR (CD_2Cl_2): δ –12.9, –13.6 (1:1.05 ratio with CuI precursor; 1.18:1 for Cu((*R*,*S*)-PPF-*t*-Bu)(I) precursor). ^{1}H NMR (CD_2Cl_2, most signals were assigned to the mixture of diastereomers, but distinct resonances for one aryl proton were observed for the individual isomers): δ 7.48 (t, J = 2, 4H, Ar), 7.24 (br, 1H, Ar (one isomer)), 7.18 (br, 1H, Ar (one isomer)), 7.14-7.04 (m, 7H, Ar), 6.98-6.90 (m, 6H, Ar), 3.71-3.57 (m, 4H, CH_2), 1.38 (36H, *t*-Bu), 1.35 (9H, *t*-Bu) 1.34 (9H, *t*-Bu).$^{13}C\{^{1}H\}$ NMR (CD_2Cl_2): δ 159.4 (d, J = 13, quat *o*-Mes*), 151.03 (quat *p*-Mes*), 151.01 (quat *p*-Mes*), 145.2 (apparent dd, J = 4, 26, quat ipso Ar), 140.6 (apparent dd, J = 13, 19, quat Ar), 131.3 (apparent dd, J = 10, 42, quat ipso Ar), 131.0 (apparent dt, J = 9, 28, Ar), 129.9 (d, J = 16, Ar), 128.7 (Ar), 128.2 (t, J = 3, Ar), 127.2 (m, Ar), 126.2 (Ar), 124.3 (t, J = 6, Ar), 39.8 (m, quat CMe_3), 37.7 (apparent dd, J = 5, 29, P-CH_2), 35.6 (quat CMe_3), 34.41 (CMe_3), 34.37 (CMe_3), 31.5 (CMe_3). As observed for the monophosphine PPhMes*(CH_2-2-naphthyl) (**3**), an apparent equilibrium for coordination to Pd prevented determination of the enantiopurity, but the samples made with chiral and CuI catalyst precursors were very similar (see the SI).

PNP Pincer Precursor 2,6-(PPhMes*CH$_2$)$_2$C$_5$H$_3$N (7) To the catalyst precursor (0.007 mmol, 10 mol % (1.3 mg of CuI, or 5.0 mg of Cu((*R*,*S*)-PPF-*t*-Bu)(I), or 5.0 mg of Cu((*R*,*S*)-CyPF-*t*-Bu)(I)) was added a solution of Mes*PH(Ph) (22.3 mg, 0.0735 mmol, 10.5 equiv) and bis(2,6-dibromomethyl)pyridine (9.3 mg, 0.035 mmol, 5.0 equiv) in 1 mL of THF. The solution was added to solid $NaOSiMe_3$ (9.0 mg, 0.077 mmol, 11 equiv). The resulting orange solution was stirred for 72 h, and a white solid formed. The reaction was monitored by $^{31}P\{^{1}H\}$ NMR spectroscopy every 24 h until only a trace of secondary phosphine remained. The solvent was removed under vacuum to give an orange solid and the residue was extracted with a 9:1 pentane/THF mixture (3 mL). The resulting orange

solution was passed through a silica column (10 cm height, 1 cm diameter), using 9:1 pentane/THF as eluent (10 mL) to give a colorless solution. The solvent was removed in vacuo to yield a colorless oil as a mixture of diastereomers (25 mg with CuI (76%, 1.1:1 dr); 22 mg with Cu((*R,S*)-PPF-*t*-Bu)(I) (78%, 1.34:1 dr); 26 mg with Cu((*R,S*)-CyPF-*t*-Bu)(I) (91%, 1.4:1 dr)).

HRMS m/z calcd for $C_{55}H_{76}NP_2$ (MH^+): 812.5453. Found: m/z 812.5432. Anal. Calcd for $C_{55}H_{75}NP_2$: C, 81.34; H, 9.31; N, 1.72. Found: C, 75.00, H, 9.03, N, 1.62. We were not able to get satisfactory elemental analyses. $^{31}P\{^1H\}$ NMR (CD_2Cl_2): δ –14.4, –14.5; dr depended on the catalyst precursor, as above. ^1H NMR (CD_2Cl_2, most signals were assigned to the mixture of diastereomers, but some distinct aryl and CH_2 resonances were observed for the individual isomers): δ 7.49 (t, J = 2, 4H, Ar), 7.43 (t, J = 7, 1H, Ar, one isomer), 7.37 (t, J = 7, 1H, Ar, one isomer), 7.18-7.11 (m, 6H, Ar), 7.08-7.05 (m, 1H, Ar), 7.04-7.00 (m, 3H, Ar), 6.97 (br d, J = 7, 1H, Ar), 6.87 (br d, J = 7, 1H, Ar), 3.99 (dd, J = 14, 1, 2H, P-CH_2, one isomer), 3.97 (dd, J = 14, 1, 2H, P-CH_2, one isomer), 3.76 (br d, J = 14, 2H, P-CH_2, one isomer), 3.73 (br d, J = 14, 2H, P-CH_2, one isomer), 1.40 (18H, *t*-Bu), 1.39 (18H, *t*-Bu) 1.34 (18H, *t*-Bu). $^{13}C\{^1H\}$ NMR (CD_2Cl_2): δ 160.3 (apparent dd, J = 21, 25, quat Ar), 159.4 (apparent dd, J = 4, 14, quat *o*-Mes*), 151.2-151.1 (br m, quat *p*-Mes*), 144.9 (apparent dd, J = 10, 27, quat Ar), 137.0 (d, J = 18, quat Ar), 131.7 (apparent dd, J = 31, 44, quat Ar), 129.9 (d, J = 16, Ar), 128.1 (Ar), 128.0 (d, J = 2, Ar), 125.9 (apparent dd, J = 3, 18, Ar), 124.2 (d, J = 7, Ar), 121.0 (d, J = 7, Ar), 40.7 (apparent dd, J = 18, 29, P-CH_2), 39.9 (d, J = 4, quat *C*Me$_3$), 35.6 (quat *C*Me$_3$), 34.4 (d, J = 7, C*Me*$_3$), 31.3 (C*Me*$_3$).

We were not able to determine the enantiopurity of **7**. The $^{31}P\{^1H\}$ NMR spectra were consistent with an equilibrium between free and Pd*-coordinated phosphine, as observed with PCP analogue **6** and monophosphine **3**, but more signals were observed and their $^{31}P\{^1H\}$ NMR chemical shifts were very different from those of the PCP analog, perhaps because of selective pyridine coordination. Spectra of bis(phosphine)/Pd* samples prepared with CuI, Cu((*R,S*)-PPF-*t*-Bu)(I), or Cu((*R,S*)-CyPF-*t*-Bu)(I) catalyst precursors were similar, suggesting that the chiral catalysts did not result in enantioselective reactions (see the SI for details).

Cu((*R,S*)-PPF-*t*-Bu)(OSiMe$_3$) (8) To "Puratronic" Cu(I) iodide (Alfa Aesar, 99.999%, 22 mg, 0.12 mmol) was added a solution of (*R,S*)-PPF-*t*-Bu (65 mg, 0.12 mmol) in 1 mL of THF-d_8. The resulting orange solution was stirred for 20 min. A solution of NaOSiMe$_3$ (17 mg, 0.15 mmol, 1.2 equiv) in 1 mL of THF-d_8 was added and the resulting solution was stirred for 10 minutes, then filtered through Celite to remove the precipitate. After NMR spectra were acquired in the original solution, the solvent was removed under vacuum to give a light orange powder (60 mg, 88%).

$^{31}P\{^1H\}$ NMR (THF-d_8, 25 °C): δ 30.6 (d, J = 163, P(*t*-Bu)$_2$), –23.5 (d, J = 163, PPh_2). ^1H NMR (THF-d_8, 25 °C): δ 8.07 (t, J = 10, 2H, Ph), 7.76 (t, J = 9, 2H, Ph), 7.46-7.31 (br m, 6H, Ph), 4.66 (1H, Cp), 4.38 (1H, Cp), 4.05 (5H, Cp), 4.03 (1H, Cp), 3.45 (m, 1H, C*H*Me), 1.96 (t, J = 7, 3H, CH*Me*), 1.30 (d, J = 13, 9H, *t*-Bu), 1.11 (d, J = 13, 9H, *t*-Bu), -0.18 (13H, OSi*Me*$_3$ in rapid exchange with free NaOSiMe$_3$). $^{13}C\{^1H\}$ NMR (THF-d_8, 25 °C): δ 136.2 (d, J = 25, quat Ar), 135.0 (d, J = 15, Ar CH), 134.5 (d, J = 16, Ar CH), 134.2 (dd, J = 9, 9, quat Ar), 130.3 (Ar CH), 130.1 (Ar CH), 129.0 (d, J = 9, Ar CH), 128.9 (d, J = 10, Ar CH), 95.0 (dd, J = 7, 21, quat Cp), 76.2 (d, J = 25, quat Cp), 75.1 (d, J = 7, Cp CH), 71.5 (d, J = 10, Cp CH), 70.7 (Cp CH), 69.2 (d, J = 6, Cp CH), 37.3 (d, J = 4, *C*Me$_3$), 35.3 (d, J = 6, *C*Me$_3$), 33.5 (*C*HMe), 31.6 (d, J = 8, C*Me*$_3$), 31.0 (d, J = 8, C*Me*$_3$), 17.3 (d, J = 5, CH*Me*), 4.7 (OSi*Me*$_3$).

Cu((*R,S*)-CyPF-*t*-Bu)(OSiMe$_3$) (9) To Cu(CyPF-*t*-Bu)(I) (10 mg, 0.013 mmol) was added a solution of NaOSiMe$_3$ (2 mg, 0.013 mmol) in 1 mL of THF-d_8. The resulting orange solution was stirred for 10 min. A white solid formed. The product was characterized by NMR spectroscopy.

$^{31}P\{^1H\}$ NMR (THF-d_8, 25 °C): δ 25.9 (d, J = 155, P(*t*-Bu)$_2$), –15.6 (d, J = 155, PCy_2). ^1H NMR (THF-d_8, 25 °C): δ 4.61 (m, 1H, Cp), 4.44 (m, 1H, Cp), 4.38 (t, J = 3, 1H, Cp), 4.22 (5H, Cp), 3.24 (apparent dq, *J* = 3, 7, 1H, C*H*Me), 2.27-2.09 (m, 6H, overlapping Cy CH and Cy CH_2), 1.98 (t, J = 7, 3H, CH*Me*), 1.90-1.76 (m, 6H, overlapping Cy CH and Cy CH_2), 1.64-1.58 (m, 5H, Cy CH_2), 1.45 (d, J = 12, 9H, *t*-Bu), 1.36-1.27 (m, 5H, Cy CH_2), 1.04 (d, J = 13, 9H, *t*-Bu), -0.18 (44H, OSi*Me*$_3$, in rapid exchange). $^{13}C\{^1H\}$ NMR (THF-d_8, 25 °C): δ 96.1 (m, quat Cp), 76.4 (d, J = 15, quat Cp), 75.2 (Cp CH), 71.8 (d, J = 7, Cp CH), 71.1 (Cp CH), 69.4 (d, J = 4, Cp CH), 40.3 (d, J = 10, Cy CH), 38.2 (d, J = 4, *C*Me$_3$), 36.4 (*C*Me$_3$), 35.2-35.1 (dd, J = 7, 14, Cy CH), 34.9 (C*H*Me), 32.6 (d, J = 12, Cy CH_2), 32.1 (t, J = 7, C*Me*$_3$), 30.5 (d, J = 6, Cy CH_2), 30.0 (d, J = 7, Cy CH_2), 29.0 (Cy CH_2), 28.9 (Cy CH_2), 28.6 (d, J = 12, Cy CH_2), 28.5 (d, J = 12, Cy CH_2), 28.2 (d, J = 9, Cy CH_2), 27.5 (d, J = 7, Cy CH_2), 26.4 (Cy CH_2), 18.5 (d, J = 4, CH*Me*), 5.5 (OSi*Me*$_3$).

Generation of Cu((*R,S*)-PPF-*t*-Bu)(PHPh(Is))(OSiMe$_3$) (11) and Cu((*R,S*)-PPF-*t*-Bu)(PPhIs) (15) To Cu((*R,S*)-PPF-*t*-Bu)(I) (10 mg, 0.01 mmol) was added PHPh(Is) (4 mg, 0.01 mmol) and NaOSiMe$_3$ (2 mg, 0.01 mmol) in 1 mL of THF, resulting in an orange solution. The products were characterized by $^{31}P\{^1H\}$ NMR spectroscopy in a mixture with the free Josiphos ligand. On standing, more unidentified impurities formed.

$^{31}P\{^1H\}$ NMR (THF, 25 °C): δ 50.1 (d, J = 55, P(*t*-Bu)$_2$ free Josiphos), 41.3 (dd, J = 73, 113, P(*t*-Bu)$_2$ phosphido **15**), 31.0 (d, J = 161, P(*t*-Bu)$_2$ phosphine-silanolate adduct **11**), –16.3 (dd, J = 113, 54, PPh_2 (**15**)), –23.2 (d, J = 161, PPh_2 (**11**)), -26.0 (d, J = 55, PPh_2 free Josiphos), –55.2 (apparent t, J = 70, PPhIs (**15**)), –83.2 (PHPh(Is) (**11**)). Selected ^{31}P NMR (THF, 25 °C): δ -83.2 (d, J = 218, PHPh(Is) (**11**)). On cooling, a 5:1 mixture of two diastereomers of phosphido complex **15** was observed. See the results and discussion and SI for more details.

Generation of Cu((*R,S*)-PPF-*t*-Bu)(PHPh(Mes))(OSiMe$_3$) (12) and Cu((*R,S*)-PPF-*t*-Bu)(PPhMes) (16) To Cu((*R,S*)-PPF-*t*-Bu)(I) (20 mg, 0.03 mmol) was added a solution of PHPh(Mes) (6 mg, 0.03 mmol) and NaOSiMe$_3$ (3 mg, 0.03 mmol) in 1 mL of THF, resulting in an orange solution.

$^{31}P\{^1H\}$ NMR (THF, 25 °C): δ 49.9 (d, J = 55, P(*t*-Bu)$_2$ free Josiphos), 40.7 (dd, J = 59, 114, P(*t*-Bu)$_2$ phosphido **16**), 31.6 (d, J = 155, P(*t*-Bu)$_2$ phosphine-silanolate adduct **12**), –15.9 (dd, J = 114, 48, PPh_2 (**16**)), –23.6 (d, J = 155, PPh_2 (**12**)), –26.1 (d, J = 55, PPh_2 free Josiphos), –42.3 (apparent t, J = 57, PPhMes (**16**)), –77.4 (PHPh(Mes) (**12**)). Selected ^{31}P NMR (THF, 25 °C): δ –77.4 (d, J_{PH} = 220, PHPh(Mes) (**12**)).

Cu((*R,S*)-PPF-*t*-Bu)(PHPh(*o*-An)(OSiMe$_3$) (13) To a solution of Cu((*R,S*)-PPF-*t*-Bu)(OSiMe$_3$) (60 mg, 0.09 mmol) in 1 mL of THF-d$_8$ was added a solution of PHPh(*o*-An) (19 mg, 0.09 mmol) in 1 mL of THF-d$_8$. The ^{31}P{^{1}H} NMR spectrum of the resulting orange solution showed the presence of four diastereomers (A-D).

^{31}P{^{1}H} NMR (THF-d$_8$, 25 °C): δ 53.5 (d, J = 54, P(*t*-Bu)$_2$ A), 42.8-42.0 (br m, P(*t*-Bu)$_2$ B and C), 39.4 (d, J = 105, P(*t*-Bu)$_2$ D), –15.4 to –15.9 (br m, PPh$_2$ B and C), –21.9 (d, J = 105, PPh$_2$ D), –22.5 (d, J = 54, PPh$_2$ A), –53.8 (PHPh(*o*-An) A-D), –54.1 (PHPh(*o*-An) A-D). When the sample was cooled to –35 °C, two broad signals were observed in the secondary phosphine region at δ –49.5 and –63.0; on further cooling to –65 °C an additional broad resonance at –68.0 appeared, as well as a low-intensity triplet peak (J = 36) at –57.1, assigned to the phosphido complex Cu((*R,S*)-PPF-*t*-Bu)(PPh(*o*-An)) (**17**). The ^{31}P NMR spectrum at –65 °C showed that the –49.5 and –63.0 resonances had J_{PH} of 228 and 304 Hz, respectively; the –68.0 signal was too broad to determine J_{PH}.

Generation of Cu((*R,R*)-*i*-Pr-DuPhos)(PHPh(Mes))(OSiMe$_3$) (14) and Cu(*R,R*)-*i*-Pr-DuPhos)(PPhMes) (18) To [Cu((*R,R*)-*i*-Pr-DuPhos)(I)]$_2$ (10 mg, 0.08 mmol) was added a solution of PHPh(Mes) (4 mg, 0.016 mmol) and NaOSiMe$_3$ (2 mg, 0.016 mmol) in 1 mL of THF, resulting in a red-orange solution.

^{31}P{^{1}H} NMR (THF, 25 °C): δ 4.6 (d, J = 65, DuPhos phosphido **18**), 2.9 (br, DuPhos phosphido **18** minor isomer), –3.4 (br, DuPhos phosphine-silanolate adduct **14**), –12.4 (free DuPhos), –35.2 (t, J = 65, PPhMes (**18**)), –76.5 (PHPh(Mes) A (**14**)), –76.6 (PHPh(Mes) B (**14**)). Selected ^{31}P NMR (THF, 25 °C): δ –76.1 (br d, J_{PH} = 228, PHPh(Mes) A (**14**)), –77.1 (br d, $J_{P\text{-}H}$ = 229, PHPh(Mes) B (**14**)).

Addition of 2-Bromomethylnaphthalene to Cu(((*R,S*)-PPF-*t*-Bu)(PPhMes) (16) Generated In Situ from Cu((*R,S*)-PPF-*t*-Bu)(I) To Cu((*R,S*)-PPF-*t*-Bu)(I) (10 mg, 0.01 mmol) was added PHPh(Mes) (3 mg, 0.01 mmol) and NaOSiMe$_3$ (2 mg, 0.01 mmol) in 1 mL of THF, resulting in a dark orange solution whose ^{31}P{^{1}H} NMR spectrum showed it contained a mixture of **12**, **16**, and free PPF-*t*-Bu. To this mixture was added 2-bromomethylnaphthalene (3 mg, 0.01 mmol), resulting in complete conversion to PPhMes(CH$_2$-2-Nap) (**19**, ^{31}P{^{1}H} NMR: δ –20.5)[26] and Cu((*R,S*)-PPF-*t*-Bu)(OSiMe$_3$) (**8**) in 5 min as monitored by ^{31}P{^{1}H} NMR spectroscopy (apparently an excess of NaOSiMe$_3$ was present on the small scale used). Free PPF-*t*-Bu and other unidentified signals were also observed. As the reaction progressed, a white precipitate formed and the solution became a light orange color.

Addition of 2-Bromomethylnaphthalene to Cu((*R,R*)-*i*-Pr-DuPhos)(PPhMes) (18) Generated In Situ from [Cu((*R,R*)-*i*-Pr-DuPhos)(I)]$_2$ To [Cu((*R,R*)-*i*-Pr-DuPhos)(I)]$_2$ (5 mg, 0.08 mmol) was added PHPh(Mes) (4 mg, 0.02 mmol) and NaOSiMe$_3$ (3 mg, 0.02 mmol) in 1 mL of THF, resulting in a dark red-orange solution, which contained two diastereomers of phosphido complex **18**, free *i*-Pr-DuPhos, and phosphine silanolate complex **14**, as well as several unidentified byproducts. To this mixture was added 2-bromomethylnaphthalene (4 mg, 0.02 mmol), resulting in complete conversion to PPhMes(CH$_2$-2-Nap) (**19**), *i*-Pr-DuPhos, and other unidentified products, as monitored by ^{31}P{^{1}H} NMR spectroscopy. As the reaction progressed, a white precipitate formed and the solution turned a pale yellow color.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website.

Additional experimental details and NMR spectra (PDF)

AUTHOR INFORMATION

Corresponding Author

* glueck@dartmouth.edu

Notes

The authors declare no competing financial interests.

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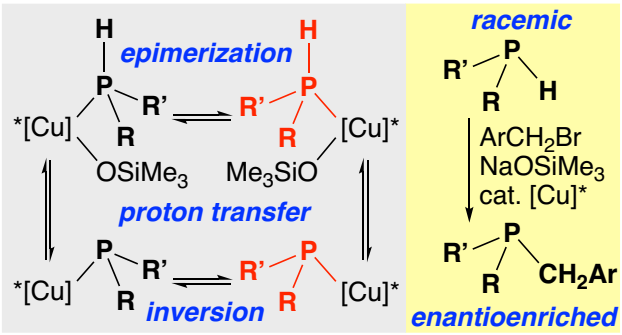

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