Homogeneous Catalysis

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Stable Cyclic (Alkyl)(Amino)Carbenes as Rigid or Flexible, Bulky, Electron-Rich Ligands for Transition-Metal Catalysts: A Quaternary Carbon Atom Makes the Difference**

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The availability of catalysts to perform specific transformations is critical for both industry and academia. Over the years, the success of homogeneous catalysis can be attributed largely to the development of a diverse range of ligand frameworks that have been used to tune the behavior of a variety of metal-containing systems. Advances in ligand design have allowed not only for improvements of known processes in terms of scope, mildness, and catalyst loadings, but also for the discovery of new selective reactions. A good illustration is given by palladium-catalyzed coupling reactions, which are applied to a wide area of endeavors ranging from synthetic organic chemistry to materials science.[1] For these catalytic processes, which represent some of the most powerful and versatile tools available for synthetic chemists, major advances have recently been reported thanks to the use of bulky, electron-rich, phosphines **A** and cyclic diaminocarbenes (N-heterocyclic carbenes (NHCs)) **B** (Figure 1).[2] These ligands stabilize the active catalytic species, and accelerate the important catalytic steps, namely oxidative addition, transmetallation, and reductive elimination. On the other hand, excessive steric hindrance can present some drawbacks for the coupling of bulky reactants.[3] To overcome this problem Glorius and co-workers have successfully developed ligands with "flexible steric bulk" using the conformational flexibility of cyclohexane.[4]

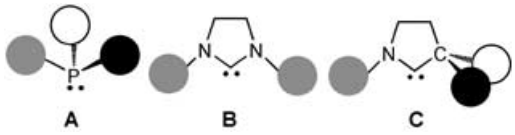
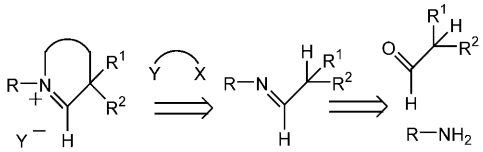


Figure 1. Schematic view of ligands **A**–**C** showing their different steric demands.

Herein we report the synthesis of stable cyclic (alkyl)(amino)carbenes (CAACs) **C** (Figure 1). The replacement of one of the electronegative amino substituents of NHCs **B** by a strong σ-donor alkyl group makes the CAAC ligands **C** even more electron-rich than **A** and **B**. Moreover, owing to the presence of a quaternary carbon atom in a position α to the carbene center, carbenes **C** feature steric environments that differentiate them dramatically from both ligands **A** and **B** (Figure 1), and amplifies flexible steric bulk effect. We show that the peculiar electronic and steric properties of carbenes **C** allow for the synthesis of CAAC-palladium complexes that are highly efficient for the catalytic α-arylation of carbonyl compounds.

Direct detection of singlet alkyl carbene compounds usually requires matrix-isolation conditions or nanosecond time-resolved laser flash photolysis techniques.[5] However, last year we reported that, provided a tertiary alkyl group is bonded to the carbene center, acyclic (alkyl)(amino)carbenes are isolable and, importantly, behave as strong σ-donors toward transition-metal centers.[6] NHCs **B** are more robust and give rise to more active catalysts, when used as ligands for transition metals, than their acyclic counterparts.[7] Therefore it was reasonable to believe that CAACs **C** would also be more stable than their acyclic variants, and would have interesting ligand properties.

The method used to prepare the precursor of acyclic (alkyl)(amino)carbenes, namely the alkylation of the corresponding enamines, is very limited in its scope. Therefore, we have designed a new synthetic approach, which is very versatile (Scheme 1). The choice of R, R^1, and R^2 substituents



Scheme 1. Retrosynthetic analysis for the preparation of CAACs.

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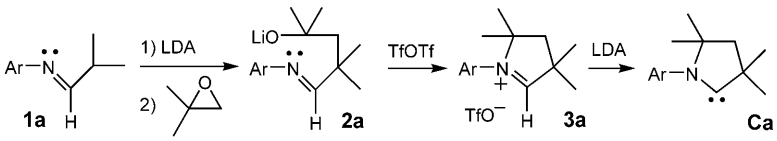
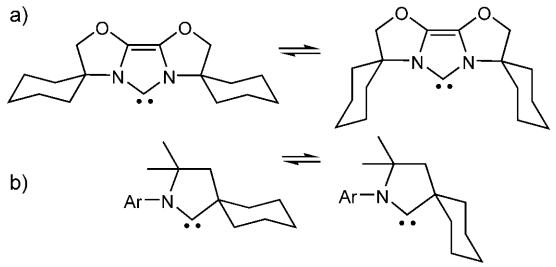
is virtually unlimited (except that R^1 and R^2 cannot be H) and the ring skeleton can be modified at will.

This synthetic strategy was first tested with imine **1a** (Scheme 2) prepared from 2,6-diisopropylaniline and the simplest aldehyde featuring a secondary alkyl substituent, 2-methylpropanal. Deprotonation of **1a** with lithium diisopropylamide (LDA) afforded the aza-allyl anion, which readily induces the ring opening of 1,2-epoxy-2-methylpropane leading to the corresponding alkoxide **2a**. Subsequent treatment with triflic anhydride (TfOTf) at −78 °C gives rise to the triflate derivative, which upon warming to room temperature affords the aldiminium salt **3a** in 58% yield (based on the imine). Lastly, deprotonation with LDA quantitatively affords carbene **Ca** as a white solid (Scheme 2). CAAC **Ca** is perfectly stable at room temperature in the solid state and in solution, for at least two weeks.



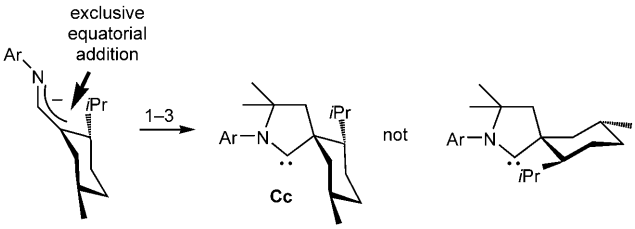
Scheme 2. Synthesis of CAAC **Ca**. Ar = 2,6-diisopropylphenyl.

The presence of the tertiary carbon center next to the carbene center offers the possibility of constructing ligands featuring different types of steric environment. Spiro-CAAC **Cb**, readily prepared in a manner similar to that used for **Ca**, but using cyclohexyl carbaldehyde, illustrates how the concept of flexible steric bulk can be incorporated into this ligand family. In fact, compared to the NHCs **B** developed by Glorius and co-workers,[4] the cyclohexane ring of **Cb** is closer to the carbene and to an ensuing metal center, and therefore the effects of the "flexible wing" should be amplified (Scheme 3).



Scheme 3. Flexible steric bulk for a) NHCs (**B**) and b) CAACs (**Cb**). Ar = 2,6-diisopropylphenyl.

In contrast to **Cb**, carbene **Cc** (Scheme 4) exemplifies the rigidity and extreme steric bulk that CAACs can provide to metal centers to which they are bound. As a starting material, we chose the imine **1c** derived from (−)-menthone. The key step of the synthesis is based on the propensity of relatively bulky reactants to approach the cyclohexane moiety from the equatorial direction. This effect is reinforced by the presence of the *iso*-propyl group, and therefore the reaction with the



Scheme 4. Stereoselective synthesis of CAAC **Cc**. 1) Dimethyloxirane; 2) TfOTf; 3) LDA; Ar = 2,6-diisopropylphenyl.

oxirane is completely diastereoselective (Scheme 4). It leads to the diastereomer affording the best protection for the carbene and the ensuing metal center to which it is bound. Moreover, in contrast with **Cb**, the chair conformation is locked. Indeed, the other chair conformation would put both the *iso*-propyl and methyl groups in unfavorable axial positions (even a boat conformation would be highly adverse). It is apparent from the molecular structure, obtained by a single-crystal X-ray diffraction study (Figure 2)[8] that the steric environment of this

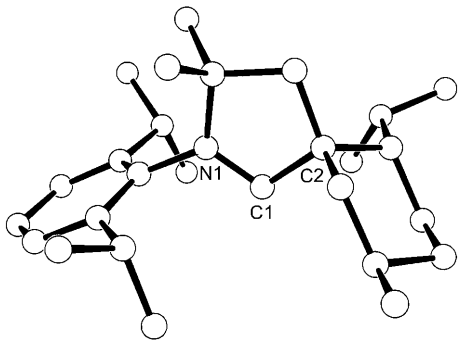


Figure 2. Molecular view of the crystal structure of **Cc**. Selected bond lengths [Å] and angles [°]: N1-C1 1.315(3), C1-C2 1.516(3); N1-C1-C2 106.54(18).

CAAC is very different from that of phosphines (described as a cone) and NHCs (defined as fan-like):[9] the locked cyclohexane moiety constitutes a "wall of protection" not only for the carbene center, but also for a metal if **Cc** is being used as a ligand (Figure 2). It is noteworthy that **Cc** is enantiomerically pure and has been prepared without time-consuming enantio- or diastereoselective separation.

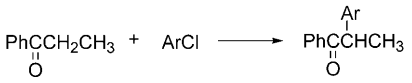
The carbonyl stretching frequencies of *cis*-[IrCl(CO)$_2$(L)] complexes are recognized as an excellent measure of the σ-donor and π-acceptor properties of the ligand L.[10] Addition of half an equivalent of [{IrCl(cod)}$_2$] (cod = 1,5-cyclooctadiene) to a THF solution of carbene **Cc** led to the formation of [IrCl(cod)(**Cc**)], which upon treatment with CO at room temperature afforded *cis*-[IrCl(CO)$_2$(**Cc**)] (**4c**) in high yield. The average value of the carbonyl stretching frequencies for complex **4c** (ν_{av}(CO) = 2013 cm^{-1}) indicates that the donor power of **Cc** is higher than that of electron-rich phosphines (PCy$_3$: ν_{av}(CO) = 2028 cm^{-1}) and even NHC ligands (2017–

2020 cm^{-1}); only the abnormal C5-bound NHCs are stronger donors (2003 cm^{-1}).[10]

The steric and electronic properties of CAACs should benefit the numerous catalytic processes which require bulky electron-rich ligands at the metal center. As an example of such a process, we chose to study the palladium-catalyzed α-arylation of ketones, discovered concurrently in 1997 by the groups of Buchwald,[11] Hartwig,[12] and Miura.[13] This reaction has not yet been achieved at room temperature with non-activated aryl chlorides; moreover there are no examples with sterically hindered di-*ortho*-substituted aryl chlorides. The use of CAAC ligands **C**, indeed, overcomes these limitations. The [PdCl(allyl)(CAAC)] complexes **5a–c** (Figure 3) were readily prepared in high yields by addition of [{Pd(allyl)(Cl)}$_2$] to the corresponding carbenes **Ca–c**, and isolated as air stable colorless crystals; they can even be purified by column chromatography on silica gel.

Table 1 summarizes the results obtained using complexes **5a–c** for the α-arylation of propiophenone, the classical substrate for the palladium-catalyzed α-arylation of ketones.[11–14] With nonhindered aryl chlorides the superior catalytic activity of CAAC complex **5c** over **5a**,**b** is demonstrated (entries 1–8). A turn over number (TON) of up to 7200 has been obtained at room temperature. This compares extremely favorably with the best TON reported to date: 4200 at 120 °C.[14c] When a di-*ortho*-substituted aryl chloride is used (entries 9–14), no catalytic activity has been observed with **5a** and **5c**, but in marked contrast **5b** is active, even at room temperature. Entries 11 and 13 indicate the thermal stability of the catalyst.

Table 1: Palladium-mediated α-arylation of propiophenone with aryl chlorides.[a]



Entry	Aryl chloride	Catalyst ([mol%])	*T* [°C]	*t* [h]	Yield [%][b]
1	PhCl	**5a** (0.5)	23	70	22
2	PhCl	**5b** (0.5)	23	70	29
3	PhCl	**5c** (0.5)	23	1	100
4	PhCl	**5c** (0.1)	23	1	83
5	PhCl	**5c** (0.01)	23	38	72
6	2-MePhCl	**5a** (0.5)	23	70	0
7	2-MePhCl	**5b** (0.5)	23	36	10
8	2-MePhCl	**5c** (0.5)	23	36	82
9	2,6-Me$_2$PhCl	**5a** (0.5)	23	70	0
10	2,6-Me$_2$PhCl	**5b** (0.5)	23	36	32
11	2,6-Me$_2$PhCl	**5b** (0.5)	70	4	56
12	2,6-Me$_2$PhCl	**5b** (1)	23	16	61
13	2,6-Me$_2$PhCl	**5b** (1)	50	20	81
14	2,6-Me$_2$PhCl	**5c** (0.5)	50	20	0

[a] Conditions: THF (1 mL), NaO*t*Bu (1.1 mmol), propiophenone (1.0 mmol), aryl chloride (1.0 mmol); all reactants (Aldrich) were used as received. [b] Yields as determined by NMR spectroscopy.

The dramatic differences observed in the catalytic activity of complexes **5a–c** can be rationalized by the different steric environments created by ligands **Ca**, **Cb**, and **Cc**. Carbene **Ca** is not sterically hindered enough to favor reductive elimination at room temperature. This step is easily promoted, for relatively small substrates, by the very rigid and bulky **Cc** ligand. However, entry 14 shows that **Cc** gives rise to a catalyst very sensitive to excessive steric hindrance. The molecular structures shown in Figure 3 clearly show that the steric environment around the metal is very similar for **5a** and **5b**, and therefore cannot explain the superior catalytic activity of **5b**. However, in solution, the cyclohexane moiety of **5b** can easily undergo a ring flip, which leads to a steric environment similar to that of **5c**.[15] This flexibility also explains the superiority of **5b** over **5c** in accommodating sterically demanding substrates in the coupling process.

Although the α-arylation of carbonyl compounds has a broad scope of application,[16] very little success has been reported with aldehydes,[17] mostly because of the competing aldol condensation. It was reasonable to believe that this side reaction could be reduced by taking advantage of the mild conditions allowed by CAAC palladium complexes. Indeed, 2-chlorotoluene is coupled with isobutanal with high efficiency at ambient temperature. Using 1 mol% of **5c**, the desired product was obtained after 16 h in 98% yield, and no evidence of aldol condensation products was observed. This is the first example of α-arylation of an aldehyde with an aryl chloride.

In recent years, several different types of stable carbene compounds have been prepared,[18] but only the "pure" σ-donor NHCs, when used as ligands, have led to highly active and robust catalysts,[19] which compete or even surpass their

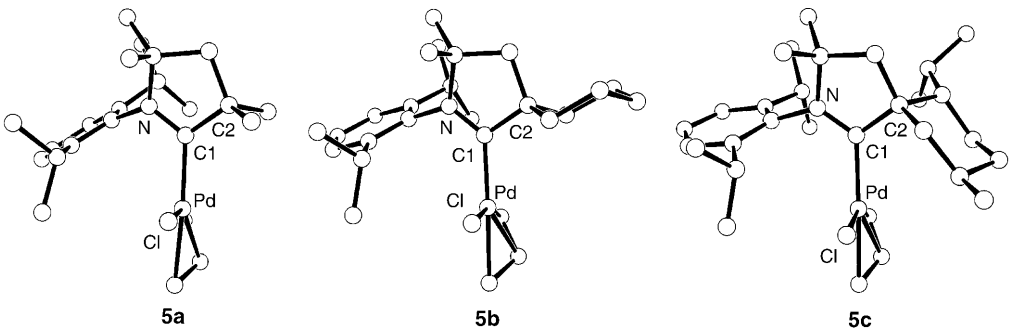


Figure 3. Molecular view of the crystal structures of **5a–c**. Selected lengths [Å] and angles [°]: **5a**: N-C1 1.3133(11), C1-C2 1.5298(12), C1-Pd 2.0246(9); N-C1-C2 108.51(8). **5b**: N-C1 1.310(4), C1-C2 1.526(4), C1-Pd 2.020(3); N-C1-C2 108.7(2). **5c**: N-C1 1.315(5), C1-C2 1.543(5), C1-Pd 2.045(4); N-C1-C2 108.8(3).

bulky, electron-rich phosphine counterparts. It is generally believed that in contrast to NHCs, Fischer-type carbenes would not survive the standard conditions of organometallic catalysis, because of the cleavage of the metal–carbon bond;[20,21] moreover they are regarded as weak σ-donors and good π-acceptors. Our work demonstrates that the readily available CAACs are strong σ-donors, weak π-acceptors, and form highly catalytically active "cyclic Fischer carbene complexes". Their unique steric and electronic properties, in addition to the broad range of structural features possible, which arise as a result of the presence of a tertiary carbon in a position α to the carbene center, makes these carbenes highly desirable as ligands for various catalytic processes, including asymmetric variants.

Experimental Section

All manipulations were performed under an inert atmosphere of argon using standard Schlenk techniques. Dry, oxygen-free solvents were employed. ^{1}H and ^{13}C NMR spectra were recorded on Varian Inova 300, 500, and Brucker Avance 300 spectrometers.

3a,**b**: A solution of LDA (4.66 g, 43.5 mmol) in Et_2O (40 mL) was added at 0 °C to a stirred solution of imine **1a** or **1b** (43.5 mmol) in Et_2O (40 mL). The solution was warmed to room temperature and stirred for 2 h. After evaporation of the solvent under vacuum, the residue was dissolved in Et_2O (80 mL), and 1,2-epoxy-2-methylpropane (4.06 mL, 45.7 mmol) was added dropwise. After stirring for 12 h at room temperature, trifluoromethane sulfonic anhydride (7.68 mL, 45.7 mmol) was added at −78 °C. The solution was warmed to room temperature and stirred for 1 h. After filtration, the residue was washed with Et_2O (80 mL). Extraction of the solid with CH_2Cl_2 (40 mL) afforded **3a**,**b** as white solids. **3a**: 58 %, m.p. 198–200 °C; ^{1}H NMR ($CDCl_3$, 25 °C, 300 MHz): $\delta = 9.48$ (s, 1H, CH), 7.53 (m, 1H, H_{ar}), 7.34 (m, 2H, H_{ar}), 2.63 (sept, 2H, C*H*CH_3, $J =$ 6.9 Hz), 2.43 (s, 2H, CH_2), 1.68 (s, 6H, CH_3), 1.54 (s, 6H, *C*H_3), 1.35 (d, 6H, CHC*H*$_3$, $J = 6.9$ Hz), 1.17 ppm (d, 6H, CHC*H*$_3$, $J = 6.9$ Hz); ^{13}C NMR (CD_3CN, 25 °C, 75 MHz): $\delta = 192.2$ (CH), 145.6, 133.1, 130.1, 126.6, 122.2 (q, $J = 321.6$ Hz), 85.8, 66.3, 48.8, 30.4, 28.5, 26.3, 26.2, 22.2 ppm. **3b**: 48 %, m.p. 268–270 °C; ^{1}H NMR (CD_3CN, 25 °C, 300 MHz): $\delta = 8.91$ (s, 1H, CH), 7.67 (m, 1H, H_{ar}), 7.52 (m, 2H, H_{ar}), 2.78 (sept, 2H, C*H*CH_3, $J = 6.9$ Hz), 2.53 (s, 2H, CH_2), 1.19–2.11 (m, 10H, CH_2), 1.59 (s, 6H, CH_3), 1.40 (d, 6H, CHC*H*$_3$, $J = 6.9$ Hz), 1.15 ppm (d, 6H, CHC*H*$_3$, $J = 6.9$ Hz); ^{13}C NMR (CD_3CN, 25 °C): $\delta =$ 191.3 (CH), 145.4, 132.9, 130.0, 126.4, 122.2 (q, $J = 321.2$ Hz), 85.0, 53.6, 45.9, 34.6, 30.2, 28.7, 26.1, 25.3, 22.1 ppm.

3c: A solution of the lithium salt of dimethylamine (1.56 g, 30.5 mmol) in THF (40 mL) was added at 0 °C to a stirred solution of imine **1c** (10.00 g, 30.5 mmol) in THF (40 mL). The solution was warmed to room temperature and stirred for 18 h. After evaporation of the solvent and then heating under vacuum at about 200 °C for 10 min, to remove the THF complexed to the lithium, the residue was dissolved in toluene (100 mL). After adding dropwise 1,2-epoxy-2-methylpropane (2.85 mL, 32.0 mmol), the solution was stirred for 12 h at room temperature. Then Tf_2O (5.39 mL, 32.0 mmol) was added at −78 °C and the suspension was allowed to warm to room temperature and stirred for 2 h. After filtration, the oily residue was washed with boiling toluene (90 mL). Extraction of the residue with CH_2Cl_2 (60 mL) afforded **3c** as a white solid, which was recrystallized in CH_2Cl_2/Et_2O at −20 °C. 6.65 g, 41 %, m.p. 258–260 °C; $[\alpha]_D^{23} = -38°$ ($CHCl_3$); ^{1}H NMR ($CDCl_3$, 25 °C, 500 MHz): $\delta = 9.73$ (s, 1H, CH), 7.53 (m, 1H, H_{ar}), 7.34 (m, 2H, H_{ar}), 2.64 (m, 3H, CH), 2.20 (m, 2H), 2.04 (m, 2H), 1.90 (m, 2H), 1.78 (m, 2H), 1.59 (s, 3H, CH_3), 1.55 (s, 3H, CH_3), 1.35 (d, 3H, CHC*H*$_3$, $J = 7.0$ Hz), 1.34 (d, 3H, CHC*H*$_3$, $J =$ 6.0 Hz), 1.21 (d, 3H, CHC*H*$_3$, $J = 6.5$ Hz), 1.17 (d, 3H, CHC*H*$_3$, $J =$ 6.0 Hz), 1.06 (d, 3H, CHC*H*$_3$, $J = 7.0$ Hz), 1.00–1.10 (m, 2H), 0.94 (d, 3H, CHC*H*$_3$, $J = 6.5$ Hz), 0.83 ppm (d, 3H, CHC*H*$_3$, $J = 6.5$ Hz); ^{13}C NMR ($CDCl_3$, 25 °C, 125 MHz): $\delta = 192.64$ (CH), 144.7, 144.5, 131.7, 129.0, 125.6, 125.1, 120.6 (q, $J = 321.6$ Hz), 81.6, 58.5, 52.2, 51.0, 45.4, 34.7, 29.9, 29.5, 29.2, 28.1, 27.1, 26.7, 25.5, 22.8, 22.7, 22.3, 22.2, 22.1, 18.7 ppm.

Ca–Cc: A 1/1 mixture of LDA and iminium salt **3** (5.0 mmol) was cooled to −78 °C and THF was added (30 mL). The suspension was warmed to room temperature and stirred for 30 min. After evaporation of the solvent under vacuum, a solid residue containing the corresponding carbene **C** and LiOTf was obtained and used for the complexation reaction without further purification, except for **Cc**. In this case, the solid residue was extracted with hexane (30 mL), and after evaporation of the solvent under vacuum, **Cc** was obtained as a white microcrystalline solid. **Ca**: ^{13}C NMR ([D$_8$]THF, 25 °C, 125 MHz): $\delta = 304.2$ (C), 145.8, 137.5, 128.0, 123.8, 82.5, 57.7, 50.3, 29.1, 28.9, 27.5, 21.7 ppm. **Cb**: ^{13}C NMR ([D$_8$]THF, 25 °C, 125 MHz): $\delta = 309.4$ (C), 145.8, 137.8, 127.9, 123.6, 81.2, 63.3, 47.7, 35.8, 29.3, 29.1, 26.4, 23.0, 21.5 ppm. **Cc**: 92 %, m.p. 115 °C; $[\alpha]_D^{23} = +113°$ (hexane); ^{1}H NMR (C_6D_6, 25 °C, 500 MHz): $\delta = 7.13$–7.25 (m, 3H, H_{ar}), 3.18 (sept, 2H, C*H*CH_3, $J = 6.9$ Hz), 2.54–2.78 (m, 2H), 2.11 (m, 1H), 1.72–1.97 (m, 4H), 1.41 (dd, 1H, $J = 12.3$ and $J = 3.3$ Hz), 1.11–1.27 (m, 21H), 1.06 (d, 3H, CHC*H*$_3$, $J = 6.9$ Hz), 1.02 (d, 3H, CHC*H*$_3$, $J =$ 6.9 Hz), 0.96 ppm (3H, CHC*H*$_3$, $J = 6.6$ Hz); ^{13}C NMR ([D$_8$]THF, 25 °C, 125 MHz): $\delta = 319.0$ (C), 146.6, 145.7, 138.1, 127.6, 123.8, 123.3, 79.7, 69.4, 53.1, 52.0, 48.0, 36.9, 30.2, 29.8, 29.1, 29.0, 28.6, 27.7, 27.0, 25.4, 24.1, 23.6, 22.8, 21.9, 21.2, 18.7 ppm.

4c: A solution of carbene **Cc** (0.34 g, 0.90 mmol) in THF (5 mL) was added at −78 °C to a stirred THF solution (5 mL) of [{IrCl(cod)}$_2$] (0.27 g, 0.41 mmol). The solution was warmed to room temperature and stirred for 3 h. After evaporation of the solvent under vacuum, the residue was washed with hexane (15 mL), dissolved in THF (5 mL), and carbon monoxide was bubbled through the solution (45 min) at room temperature. After evaporation of the solvent under vacuum, carbene complex **4c** was obtained as a brown powder. 0.42 g, 71 %; ^{1}H NMR ($CDCl_3$, 25 °C, 300 MHz): $\delta = 7.55$ (m, 1H, H_{ar}), 7.36 (m, 2H, H_{ar}), 2.61–2.76 (m, 3H), 2.38 (d, 1H, $J = 14.4$ Hz), 2.06–2.24 (m, 3H), 1.67–1.95 (m, 6H), 1.64 (s, 3H), 1.60 (s, 3H), 1.36 (d, 6H, CHC*H*$_3$, $J = 6.6$ Hz), 1.19–1.27 (m, 6H), 1.08 (d, 3H, CHC*H*$_3$, $J =$ 6.9 Hz), 0.97 (d, 3H, CHC*H*$_3$, $J = 5.4$ Hz), 0.85 ppm (d, 3H, CHC*H*$_3$, $J = 6.9$ Hz); ^{13}C NMR ($CDCl_3$, 25 °C, 75 MHz): $\delta = 191.3$ (CO), 190.9 (C), 167.8 (CO), 144.8, 144.6, 132.3, 129.0, 126.1, 125.6, 82.4, 58.7, 58.6, 52.3, 51.1, 45.8, 34.6, 30.4, 30.1, 29.7, 28.6, 27.6, 27.4, 26.6, 23.3, 23.0, 22.9, 22.5, 22.2, 19.4 ppm. IR (CH_2Cl_2): $\tilde{\nu} =$ 2055, 1971 (ν(CO)) cm^{-1}.

5a–c: A solution of carbene **C** (5.2 mmol) in THF (15 mL) was added at −78 °C to a stirred solution of [{Pd(allyl)(Cl)}$_2$] (0.95 g, 2.6 mmol) in THF (15 mL). The solution was warmed to room temperature and stirred for 3 h. After evaporation of the solvent under vacuum, the solid residue was washed with hexane (40 mL). Extraction with CH_2Cl_2 (20 mL) afforded a gray solid, which was recrystallized in THF (**5a**) or hexane (**5b**,**c**) at −20 °C. Carbene complexes **5** were obtained as colorless crystals. **5a**: 71 %, m.p. 162–163 °C; ^{1}H NMR ($CDCl_3$, 25 °C, 300 MHz): $\delta = 7.27$–7.42 (m, 3H, H_{ar}), 5.05 (m, 1H, H_{allyl}), 4.18 (d, 1H, H_{allyl}, $J = 7.5$ Hz), 3.19 (m, 3H, C*H*CH_3 and 2H_{allyl}), 3.01 (m, 1H, C*H*CH_3), 2.02 (s, 3H, H_{allyl}, CH_2), 1.64 (s, 6H, *C*H_3), 1.23–1.40 ppm (m, 18H, CH_3); ^{13}C NMR ($CDCl_3$, 25 °C, 75 MHz): $\delta = 267.4$ (C), 146.5, 135.8, 129.1, 125.1, 115.5, 81.5, 76.8, 57.5, 50.5, 48.6, 31.7, 30.6, 29.3, 28.6, 28.1, 27.5, 25.1 ppm. **5b**: 74 %, m.p. 176–178 °C; ^{1}H NMR ($CDCl_3$, 25 °C, 300 MHz): $\delta = 7.21$–7.63 (m, 3H, H_{ar}), 5.04 (m, 1H, H_{allyl}), 4.18 (d, 1H, H_{allyl}, $J = 7.5$ Hz), 3.29 (m, 1H, C*H*CH_3), 3.15 (m, 2H, H_{allyl}), 2.98 (m, 1H, C*H*CH_3), 2.45 (m, 2H, CH_2), 1.22–2.05 (m, 17H, H_{allyl}, CH_2, CH_3), 1.30 ppm (d, 12H, CHC*H*$_3$, $J = 6.9$ Hz); ^{13}C NMR ($CDCl_3$, 25 °C, 75 MHz): $\delta = 267.8$ (C), 146.5, 136.3, 129.0, 125.1, 115.6, 80.5, 77.0, 62.9, 48.3, 45.7, 38.8, 37.2, 31.3, 29.5, 28.6, 28.0, 27.0, 25.4, 25.3, 22.9, 22.4 ppm. **5c**: 70 %, m.p. 157–159 °C; $[\alpha]_D^{23} = -1°$ ($CHCl_3$); ^{1}H NMR ($CDCl_3$, 25 °C, 300 MHz): $\delta = 7.20$–7.38 (m, 3H, H_{ar}), 5.04 (m, 1H, H_{allyl}), 4.21 (d, 1H, H_{allyl}, $J = 7.5$ Hz), 3.70 (sept, 1H, C*H*CH_3, $J = 6.3$ Hz), 3.15 (d,

1H, H_{allyl}, $J = 14.1$ Hz), 2.82–2.98 (m, 4H), 2.32 (m, 1H), 1.70–2.09 (m, 7H), 1.35–1.45 (m, 8H), 1.30 (d, 6H, $CHCH_3$, $J = 6.6$ Hz), 1.29 (s, 3H), 1.20 (d, 3H, $CHCH_3$, $J = 6.9$ Hz), 0.99 (t, 6H, $CHCH_3$, $J = 6.9$ Hz), 0.93 ppm (d, 3H, $CHCH_3$, $J = 6.6$ Hz); ^{13}C NMR ($CDCl_3$, 25 °C, 75 MHz): $\delta = 272.0$ (C), 148.3, 145.6, 137.5, 129.0, 126.4, 124.7, 114.9, 78.7, 78.0, 67.4, 54.2, 52.0, 51.2, 48.1, 33.7, 33.6, 30.7, 30.1, 29.2, 29.0, 28.6, 28.0, 27.2, 26.0, 25.7, 23.8, 22.4, 20.9 ppm.

α-Arylation procedure: Glass vials were charged under inert atmosphere in the glovebox with NaO*t*Bu (1.1 mmol) in THF (0.5 mL). Then a mixture of the palladium catalyst (see Table 1 for amounts), aryl halide (1.0 mmol) and propiophenone or isobutanal (1.0 mmol) in THF (0.5 mL) was added at room temperature. Then the reaction were stirred at the temperature for the period of time indicated in Table 1. The reactions were quenched with aqueous solution of NH_4Cl and extracted with Et_2O. The organic layer was dried over $MgSO_4$. All compounds were identified by ^{1}H NMR spectroscopy. The reported yields are determined by NMR spectroscopy.

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