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Oxidation-resistant, sterically demanding phenanthrolines as supporting ligands for copper(I) nitrene transfer catalysts†

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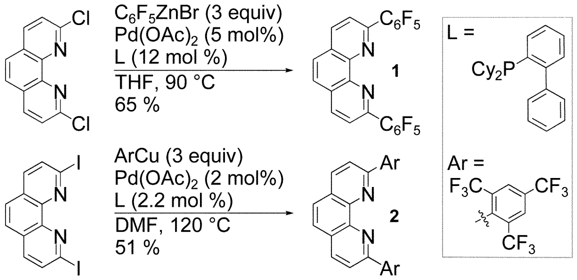
New 1,10-phenanthroline ligands have been synthesized with C_6F_5– or 2,4,6-$(CF_3)_3C_6H_2$– groups in the 2- and 9-positions; a cationic copper(I) complex of the latter catalyses nitrene transfer to the C–H bonds of electron-rich arenes.

The efficient and selective functionalisation of carbon–hydrogen bonds represents an ongoing challenge in inorganic and organic chemistry.[1] We are interested in low-coordinate late transition metal complexes as catalysts for atom- and group-transfer reactions of this type. Ligands such as 2,9-diphenyl-1,10-phenanthroline,[2] and its 2,9-dimesityl analogue,[3] project considerable steric bulk about the metal, but expose C–H bonds to the metal center. We report herein the synthesis of two new 1,10-phenanthroline ligands, substituted in the 2- and 9-positions with heavily fluorinated aryl groups[4] to avoid oxidative ligand modification.[5] Copper(I) complexes of both phenanthrolines have been prepared and structurally characterized; the more sterically demanding ligand gives rise to a reactive precatalyst for the transfer of a nitrene group from iminoiodinanes to the C–H bonds of electron-rich arenes.[6]

The new phenanthrolines were prepared by cross-coupling reactions, using $Pd(OAc)_2$ precatalyst and the 2-(dicyclohexylphosphino)biphenyl ligand developed by Buchwald and coworkers[7] (Scheme 1). The reaction of 2,9-dichloro-1,10-phenanthroline[8] with C_6F_5ZnBr[9] affords 2,9-bis(pentafluorophenyl)-1,10-phenanthroline (**1**) in good yield. The Negishi coupling has been used previously to prepare a variety of 2,9-diaryl-1,10-phenanthrolines.[10] The reaction of 2,9-diiodo-1,10-phenanthroline[11] with 2,4,6-$(CF_3)_3C_6H_2Cu$,[12] prepared *in situ* by lithiation of 2,4,6-$(CF_3)_3C_6H_3$ followed by addition of CuI, affords 2,9-bis-[2′,4′,6′-tris(trifluoromethyl)phenyl]-1,10-phenanthroline (**2**).

Reaction of **1** with CuI in CH_2Cl_2 at ambient temperature (Scheme 2) results in the formation of a homoleptic complex $[(\mathbf{1})_2Cu]^+$, crystallised as its SbF_6^- salt **3**.† The X-ray crystal structure of **3** (Fig. 1)‡shows bond lengths and bite angles similar to those in copper(I) complexes of 2,9-diphenyl-1,10-phenanthroline;[2] however, one phenanthroline is canted, permitting a π-stacking interaction with a pentafluorophenyl group; the distance between rings is 3.343(5) Å.

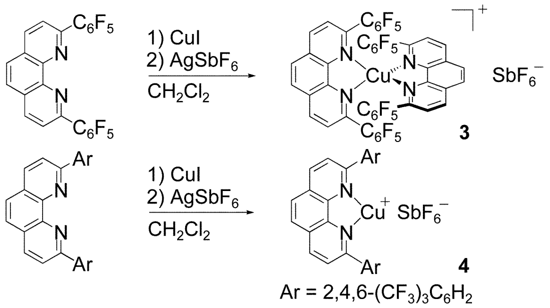
Ligand **2** presents considerably greater steric demand than **1**, and reacts with CuI in CH_2Cl_2 to afford trigonal **2**·CuI. The iodide ligand is readily abstracted by $AgSbF_6$, and the product after drying is the solvent-free $[\mathbf{2}\cdot Cu]^+ SbF_6^-$ (**4**), characterised by NMR and elemental analysis.§This complex has resisted efforts at crystallisation; however, exposure of a concentrated CH_2Cl_2 solution of **4** to a small concentration of benzene vapor results in crystallisation of the η^2-benzene adduct **4′** (Fig. 2).‡ Like other copper(I)–benzene adducts,[13] **4′** shows no substantial lengthening of the coordinated C–C bond.



Scheme 1 Synthesis of fluorinated 2,9-diaryl-1,10-phenanthrolines.

Solutions of complex **4**, on addition of the reagent (*p*-toluenesulfonylimino)phenyliodinane (PhINTs),[14] form a reactive green intermediate, with liberation of free iodobenzene. We have as yet been unable to preclude extensive decomposition during the isolation of this intermediate, possibly a cationic (sulfonylimido)-copper(III) complex. Instead, we have investigated its activity in the transfer of tosylnitrene to arene C–H bonds.

The reaction of PhINTs with anisole[15] (17 equiv) in $PhCF_3$ solution, catalysed by **4** (0.5 mol%), resulted in the rapid



Scheme 2 Synthesis of copper(I) complexes **3** and **4**.

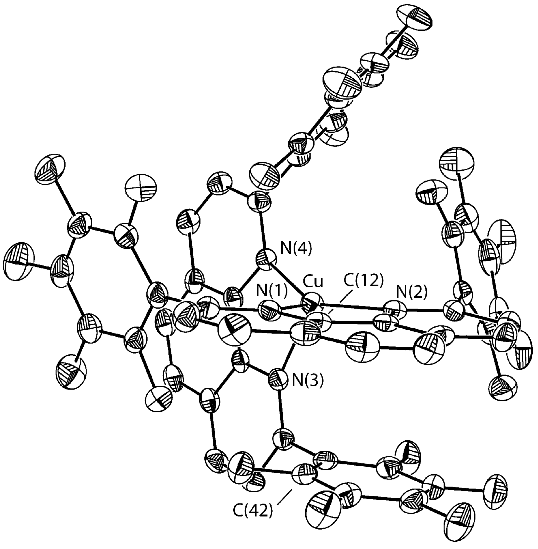


Fig. 1 Representation of **3**, shown as 50% ellipsoids. The SbF_6^- ion, one molecule of CH_2Cl_2 and hydrogen atoms have been omitted for clarity. Selected interatomic distances (Å) and bond angles (°): Cu–N(1) 2.109(3), Cu–N(2) 2.025(3), Cu–N(3) 2.079(3), Cu–N(4) 2.048(3), C(12)–C(42) 3.343(5); N(1)–Cu–N(2) 83.39(11), N(3)–Cu–N(4) 82.77(11), N(1)–Cu–N(3) 102.6(11), N(2)–Cu–N(3) 119.89(11).

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† Electronic Supplementary Information (ESI) available: Synthesis of **1–4′**, with spectroscopic and analytical details; crystallographic data plus additional structures. See http://www.rsc.org/suppdata/cc/b4/b404515g/

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dissolution of the iminoiodinane, with the formation of *o*- and *p*-sulfonamidation products, $TsNH_2$, and poorly soluble oligomers that were removed during NMR and GC-MS sample preparation. The substrate 1,3-dimethoxybenzene was chosen next, to sidestep temporarily the issue of *o*/*p* selectivity, and to examine whether the desired reaction would occur more readily with this doubly activated nucleus, minimizing the subsequent side-reactions (Scheme 3).[¶]Indeed, the reaction of PhINTs with this substrate (20 equiv in $PhCF_3$ at ambient temperature), catalysed by **4** (1.8 mol%) led to the formation of *p*-tosyl-1,3-dimethoxyaniline in an isolated yield of 63% based on iminoiodinane.

A change in stoichiometry resulted in a notably different outcome. With arene as the limiting reagent, the major product was the *N*,*N*-diarylsulfonamide. Only a trace of monoarylsulfonamide was observed; the other products appear to be sulfonated oligoarylamines. This seemingly paradoxical result suggests that the initially formed *N*-arylsulfonamide can be activated under the reaction conditions to generate a nitrogen-based electrophile.

In conclusion, we have prepared new 1,10-phenanthroline ligands substituted with heavily fluorinated aryl rings to confer steric bulk while resisting oxidation. With the C_6F_5-substituent, the ligand is small enough to form a homoleptic copper(I) complex, whereas the larger 2,4,6-$(CF_3)_3C_6H_2$-substituted ligand supports the formation of a reactive copper(I) cation. This complex catalyses nitrene transfer to the C–H bonds of an electron-rich arene, leading to either of two major products depending on the reaction stoichiometry. Near-future goals include the elucidation of relevant reaction mechanisms, and the development of more versatile arene functionalization reactions.

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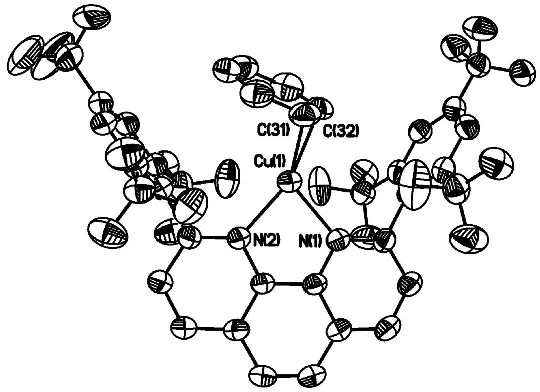
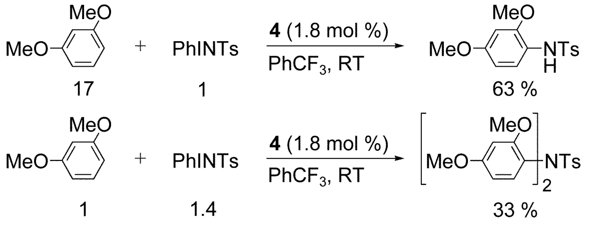


Fig. 2 Representation of **4′**, shown as 50% ellipsoids. For clarity, the SbF_6^- ion, solvent, and hydrogen atoms have been omitted, and only one molecule in the asymmetric unit is shown. A more extensive structure, showing π-stacking interactions among the cations, is available in the ESI.[†] Selected interatomic distances (Å) and bond angles (°): Cu(1)–N(1) 2.108(4), Cu(1)–N(2) 2.026(4), Cu(1)–C(31) 2.232(5), Cu(1)–C(32) 2.113(5), C(31)–C(32) 1.397(9); N(1)–Cu(1)–N(2) 82.71(15), N(1)–Cu(1)–C(31) 127.1(2), N(1)–Cu(1)–C(32) 117.2(2).



Scheme 3 Divergent outcomes for nitrene transfer to C–H bonds.

Notes and references

[‡] *Crystal data.* **3**: $C_{49}H_{14}N_4F_{26}Cl_2CuSb$, M = 1408.83, triclinic, $P\bar{1}$, a = 12.5042(13) Å, b = 14.2178(15) Å, c = 14.2393(15) Å, α = 74.479(2)°, β = 85.194(2)°, γ = 74.395(2)°, V = 2349.1(4) Å^3, Z = 2, D_{calc} = 1.992 Mg m^{-3}, MoKα λ = 0.71073 Å, T = 193 K, μ = 1.289 mm^{-1}. A total of 9642 reflections were collected in the θ range 1.97–23.30° of which 6649 were unique (R_{int} = 0.0338). No absorption correction was applied. The least squares refinement converged normally with residuals of R (based on F) = 0.0355, $wR2$ (based on F^2) = 0.0895, and GOF = 1.041 based on $I > 2\sigma(I)$.

4′: $C_{37}H_{18}N_2F_{24}Cl_2CuSb$, M = 1202.72, triclinic, $P\bar{1}$, a = 12.8498(11) Å, b = 17.2274(14) Å, c = 19.3942(16) Å, α = 88.865(2)°, β = 85.991(2)°, γ = 72.624(2)°, V = 4087.3(6) Å^3, Z = 4, D_{calc} = 1.955 Mg m^{-3}, MoKα λ = 0.71073 Å, T = 194 K, μ = 1.455 mm^{-1}. A total of 25968 reflections were collected in the θ range 1.62–28.32° of which 18329 were unique (R_{int} = 0.0186). No absorption correction was applied. The least squares refinement converged normally with residuals of R (based on F) = 0.0687, $wR2$ (based on F^2) = 0.1748, and GOF = 1.124 based on $I > 2\sigma(I)$.

CCDC 234760 and 234762. See http://www.rsc.org/suppdata/cc/b4/b404515g/ for crystallographic data in .cif or other electronic format.

[§] *Synthesis and characterization data for* **4**: Reactions were carried out at ambient temperature, in dried solvents under inert atmosphere. CuI (1.05 mmol) and **2** (0.696 mmol) were stirred overnight in CH_2Cl_2 (7 mL). Filtration of the mixture and concentration *in vacuo* afforded **2**·CuI as a red powder in 80% yield. The reaction of **2**·CuI (0.210 mmol) with $AgSbF_6$ (0.216 mmol) in CH_2Cl_2 (5 mL) for 5 min, followed by filtration and concentration *in vacuo*, afforded **4** as a yellow powder in 87% yield. ^1H NMR (300 MHz, acetone-d_6): δ 9.20 (d, J = 8.4 Hz, 2H), 8.63 (s, 4H), 8.57 (s, 2H), 8.50 (d, J = 8.4 Hz, 2H). ^{19}F NMR (282 MHz, acetone-d_6): δ −57.14 (s, 12 F), −62.90 (s, 6F). Anal. calcd for $C_{30}H_{10}N_2F_{24}CuSb$: C, 34.66; H, 0.97; N, 2.69. Found: C, 34.46; H, 1.00; N, 2.65%.

[¶] *General procedure for sulfonamidations*: Reactions were carried out at ambient temperature, in dried solvent under inert atmosphere. PhINTs and activated 3 Å molecular sieves were suspended, and catalytic amounts of **4** dissolved, in $PhCF_3$. 1,3-Dimethoxybenzene was added *via* syringe. Upon completion of the reactions, the mixtures were concentrated *in vacuo* and the organic products isolated by column chromatography on silica gel.

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