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Redox-Active Ligand-Mediated Oxidative Addition and Reductive Elimination at Square Planar Cobalt(III): Multielectron Reactions for Cross-Coupling

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Abstract: Square planar cobalt(III) complexes with redox-active amidophenolate ligands are strong nucleophiles that react with alkyl halides, including CH_2Cl_2, under gentle conditions to generate stable square pyramidal alkylcobalt(III) complexes. The net electrophilic addition reactions formally require $2e^-$ oxidation of the metal fragment, but there is no change in metal oxidation state because the reaction proceeds with $1e^-$ oxidation of each amidophenolate ligand. Although the four-coordinate complexes are very strong nucleophiles, they are mild outer-sphere reductants. Accordingly, addition of alkyl- or phenylzinc halides to the five-coordinate organometallic complexes regenerates the square planar starting materials and extrudes C−C coupling products. The net $2e^-$ reductive elimination reaction also occurs without a oxidation state change at the cobalt(III) center. Together these reactions comprise a complete, well-defined cycle for cobalt Negishi-like cross-coupling of alkyl halides with organozinc reagents.

The utility of palladium in cross-coupling catalysis derives from its ability to mediate $2e^-$ oxidative addition and reductive elimination steps for selective assembly of C−C bonds.[1] Because later first-row metal ions typically exist in oxidation states that vary by only $1e^-$, they are often prone to radical reactions with organic substrates.[2] Accordingly, development of base metal catalysts for selective cross-coupling cycles requires strategies to effect $2e^-$ redox reactions over potentially competing $1e^-$ pathways.[3] An emerging approach to multielectron chemistry employs redox "noninnocent" ligands as reservoirs of electrons for bond-making and bond-breaking reactions at coordinatively unsaturated metals.[2,4] We have utilized this strategy to prepare square planar cobalt complexes that are strong nucleophiles but mild $2e^-$ reductants. We report here how these properties facilitate well-defined $2e^-$ pseudo-oxidative addition and reductive elimination reactions at cobalt(III), comprising both steps of a catalytic cycle for Negishi-like cross-coupling of alkyl halides with alkyl- and arylzinc reagents.

The ability of amidophenolate ligands to deliver electrons for bond-forming redox reactions at square planar cobalt(III) centers was previously demonstrated in reactions of $[Co^{III}(ap^{Ar})_2]^-$ (where $[ap^{Ar}]^{2-}$ is $[ap^{Ph}]^{2-}$ = 2,4-di-*tert*-butyl-6-(phenylamido)phenolate or $[ap^{iPr}]^{2-}$ = 2,4-di-*tert*-butyl-6-(2,6-diisopropylphenylamido)phenolate) with chlorine electrophiles.[5] During the course of these studies, we observed that addition of excess CH_2Cl_2 to purple CH_3CN solutions containing the $[Co^{III}(ap^{Ph})_2]^-$ anion gave quantitative conversion to a bright green material over hours at 25 °C. Electrospray ionization mass spectra (ESI-MS) of THF solutions containing the green product showed a molecular ion at 698 *m*/*z* that was shifted to 700 *m*/*z* when the reaction was performed with CD_2Cl_2 in place of CH_2Cl_2, corresponding to the molecular weights of the $[Co^{III}(ap^{Ph})_2]^-$ reactant and a $[CH_2Cl]$ or $[CD_2Cl]$ fragment. Green crystals of the protio material were obtained from concentrated $CH_3CN-CH_2Cl_2$ solution. The X-ray structure contains a square pyramidal chloromethyl complex (Figures 1, S1). As compared to $[Co^{III}(ap^{Ph})_2]^-$, the aminophenol ligand metrical data exhibit systematic geometrical changes that are characteristic of a change in ligand oxidation state. In particular, the contracted C−O and C−N bond distances and the quinoid-like pattern of four long and two short C−C bond distances about the aminophenol ring (Figure 1b) match those typical for $[isq^{Ph}]^{\bullet-}$ ($[isq^{Ph}]^{\bullet-}$ = 2,4-di-*tert*-butyl-6-(phenylimino)semiquinonate),[6] suggesting that the product is best described as $Co^{III}(CH_2Cl)(isq^{Ph})_2$. This formulation implies that the reaction occurs with a net $2e^-$ oxidation of the $[Co^{III}(ap^{Ph})_2]^-$ fragment, but the oxidation state of the cobalt center is unchanged because each ligand supplies one electron (Scheme 1a).

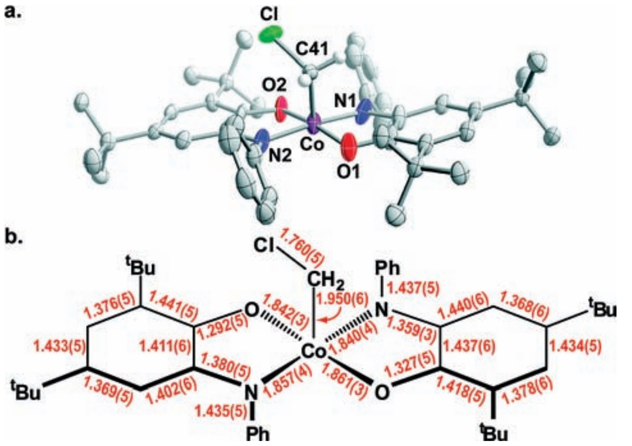

Figure 1. Solid-state structures of (a) $Co^{III}(CH_2Cl)(isq^{Ph})_2$ drawn with 50% probability ellipsoids. The $[isq^{Ph}]^{\bullet-}$ ligand hydrogen atoms are omitted for clarity. (b) Schematic of selected bond lengths (Å) drawn to correspond to Figure 1a.

THF solutions of $Co^{III}(CH_2Cl)(isq^{Ph})_2$ are stable for days in the dark at 25 °C but degrade in light to cleanly afford $Co^{III}(ap^{Ph})(isq^{Ph})$, the product of $Co-CH_2Cl$ homolysis.[7] Accordingly, when monitored at wavelengths >700 nm, the reaction of CH_2Cl_2 with $[Co^{III}(ap^{Ph})_2]^-$ in CH_3CN exhibits clean pseudo-first-order kinetics with an isosbestic point at 911 nm (Figure S2).

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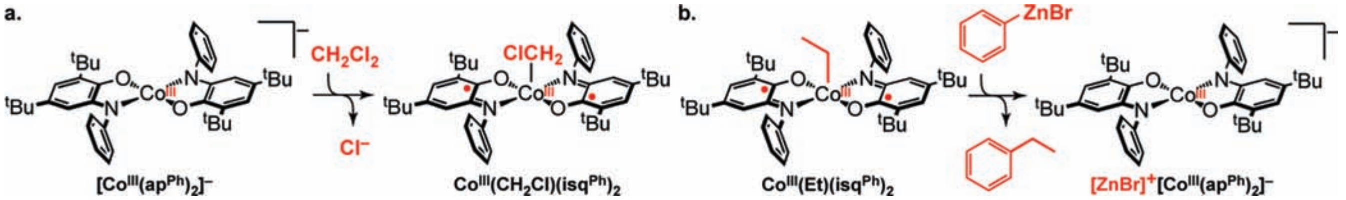
Scheme 1



Addition of 1 equiv of EtBr to $Na[Co^{III}(ap^{Ph})_2]$ in CH_3CN similarly yields a green, light-sensitive, square pyramidal ethyl complex suitable for analysis by X-ray diffraction. As in the reaction with CH_2Cl_2 described above, systematic changes in the C−O, C−N, and C−C bond distances (Figure 2) indicate that the amidophenolate chelates in $[Co^{III}(ap^{Ph})_2]^-$ are each oxidized by $1e^-$, so the product is best formulated as $Co^{III}(Et)(isq^{Ph})_2$. Solid $Co^{III}(Et)(isq^{Ph})_2$ is stable for >2 d in the dark at 25 °C, and the UV−vis spectrum of a THF solution is unchanged over 4 h at 25 °C, suggesting that the five-coordinate alkyl complexes are relatively inert to β-hydrogen elimination.

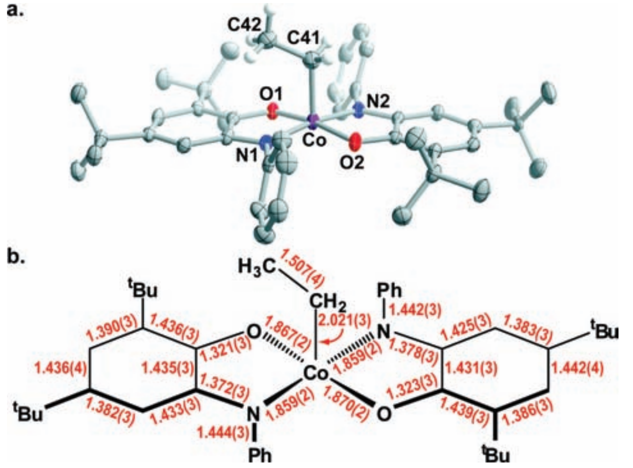
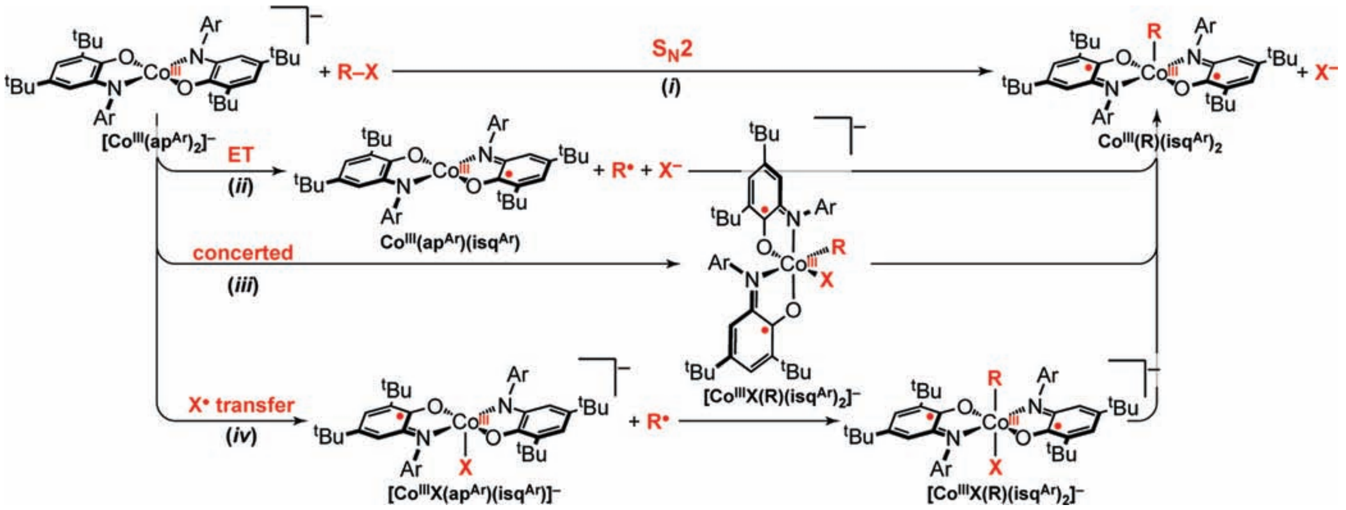


Figure 2. Solid-state structures of (a) $Co^{III}(Et)(isq^{Ph})_2$ drawn with 50% probability ellipsoids. The $[isq^{Ph}]^{\bullet-}$ ligand hydrogen atoms are omitted for clarity. (b) Schematic of selected bond lengths (Å) drawn to correspond to Figure 2a.

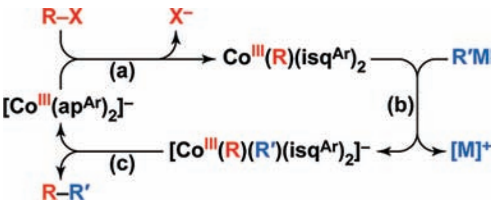
A comparison of the relative rates of organohalide addition to $[Co^{III}(ap^{Ph})_2]^-$ revealed several pertinent trends: (1) Primary alkyl halides react with $[Co^{III}(ap^{Ph})_2]^-$ to afford the corresponding alkylcobalt(III) complexes, and the relative rates of the reactions parallel the lability of the halide. For instance, addition of 5 equiv of CH_3I to 0.01 M $[Co^{III}(ap^{Ph})_2]^-$ in CH_3CN affords quantitative conversion to $Co^{III}(CH_3)(isq^{Ph})_2$ in seconds, whereas complete reaction with CH_2Cl_2 takes ∼12 h under the same conditions. The analogous reaction with CH_2ClBr requires ∼30 min and gives exclusively the $Co^{III}(CH_2Cl)(isq^{Ph})_2$ product, as determined by ESI-MS. $[Co^{III}(ap^{Ph})_2]^-$ reacts with CH_3OTf (OTf^- = trifluoromethanesulfonate) to afford $Co^{III}(CH_3)(isq^{Ph})_2$ at a rate comparable to that of the fast reaction with CH_3I. (2) All of the addition reactions are slower with more sterically demanding carbon centers. Accordingly, reactions with EtI or EtBr form $Co^{III}(Et)(isq^{Ph})_2$ in <1 min and ∼1 h, respectively, and reaction of $[Co^{III}(ap^{Ph})_2]^-$ with isopropyl iodide requires 3 h. $PhCH_2Br$ reacts with $[Co^{III}(ap^{Ph})_2]^-$ to give $Co^{III}(CH_2Ph)(isq^{Ph})_2$ in 1 d, and >2 d are required for complete reaction with $PhCH_2Cl$. (3) No addition reaction occurs at sp^2-hybridized carbon centers. $[Co^{III}(ap^{Ph})_2]^-$ is inert to iodobenzene and vinyl bromide over weeks at 25 °C. (4) The addition reactions are highly sensitive to steric bulk at the cobalt center. For example, all alkyl halide additions to $[Co^{III}(ap^{iPr})_2]^-$ are significantly slowed relative to $[Co^{III}(ap^{Ph})_2]^-$. All of these observations are collected in Table S1.

Four mechanisms that are consistent with the UV−vis kinetics were considered for generation of $Co^{III}(R)(isq^{Ar})_2$ and X^- from $[Co^{III}(ap^{Ar})_2]^-$ and R−X (Scheme 2). Two invoke six-coordinate oxidative addition $[Co^{III}X(R)(isq^{Ph})_2]$ products as unobserved intermediates followed by rapid loss of X^-, but the data above suggest that both of these pathways involving Co−X bond formation can likely be ruled out. In particular, the rapid reaction of $[Co^{III}(ap^{Ph})_2]^-$ with CH_3OTf suggests that a radical mechanism (*iv*) of initial X• transfer is unlikely, and substrates such as CH_3I and CH_3OTf do not typically react by a concerted addition mechanism (*iii*).[8]

Scheme 2



Scheme 3



The two remaining mechanisms both invoke conversion of $[Co^{III}(ap^{Ar})_2]^-$ directly to the five-coordinate $Co^{III}(R)(isq^{Ar})_2$ product without Co−X bond formation, but these represent limits of the potential $1e^-$ vs $2e^-$ redox pathways. The observed increase in reaction rate with leaving group lability, $I^- > Br^- > Cl^-$, does not distinguish mechanism (*i*) versus (*ii*), and previously reported reactions of $Co^{III}(ap^{Ar})(isq^{Ar})$ with sources of net [Cl•] to generate $Co^{III}Cl(isq^{Ar})_2$ demonstrate the ability of $Co^{III}(ap^{Ar})(isq^{Ar})$ to function as a radical trap.[5] However, the sum of the other experimental observations does not support an electron transfer (ET) mechanism (*ii*). For example, the $[Co^{III}(ap^{iPr})_2]^-$ anion is a better $1e^-$ reductant than $[Co^{III}(ap^{Ph})_2]^-$,[5] but it reacts with alkyl halides at a significantly decreased rate. Additionally, its slow reactions with 2° alkyl halides as compared to 1° haloalkanes are inconsistent with a mechanism of initial outer-sphere ET (*ii*). Instead, this sensitivity to steric hindrance at carbon, as well as to steric encapsulation of the cobalt(III) center by the $[ap^{iPr}]^{2-}$ ligands, is most consistent with the S_N2-type mechanism (*i*) wherein Co−R bond formation requires direct attack of the nucleophilic cobalt center on the alkyl halide electrophile.[9,10]

The accessibility of the alkylcobalt(III) complexes prompted us to pursue reductive C−C bond-forming reactions with organozinc compounds. Treating $Co^{III}(Et)(isq^{Ph})_2$ with PhZnBr (2−10 equiv) in a 1:1 CH_3CN/THF solution results in an immediate discharge of the green color and formation of the reduced cobalt fragment $[Co^{III}(ap^{Ph})_2]^-$ (Scheme 1b).[11] Complete consumption of 0.01 M $Co^{III}(Et)(isq^{Ph})_2$ requires >6 equiv of PhZnBr, presumably because phenyl transfer is sterically disfavored (Scheme 3b). GC-MS analysis of the reaction mixtures shows the expected cross-coupling product ethylbenzene in 10−15% yield (Table S2). The analogous reactions with hexylzinc bromide similarly afford *n*-octane in 5−15% yield. Both reactions give small quantities of the corresponding homocoupling byproducts, biphenyl (<2%) and dodecane (<7%). Notably, addition of greater excesses of RZnX gives nonstatistical product distributions, with increased yields of the cross-coupling products relative to homocoupling.[12] These data imply that the C−C bond-forming reactions do not occur by radical Co−Et homolysis at $Co^{III}(Et)(isq^{Ph})_2$. Studies to elaborate the reductive elimination mechanism, and to optimize conditions for catalytic cross-coupling (Scheme 3), are in progress.

In sum, the ability of redox-active ligands to facilitate both $2e^-$ pseudo-oxidative addition and reductive elimination reactions at mononuclear square planar cobalt(III) complexes is predicated on two properties: (1) The $[Co^{III}(ap^{Ar})_2]^-$ species are very strong nucleophiles, reminiscent of "supernucleophilic" cobaloxime(I) complexes and square planar iridium(I) compounds that undergo S_N2-type oxidative addition of R−X.[7,13] However, these cobalt(III) anions are unusual nucleophiles. They have diradical $S = 1$ ground states,[5] and their reactions with haloalkanes occur without a change in oxidation state at the cobalt(III) centers because the redox-active aminophenol-derived ligands in $[Co^{III}(ap^{Ar})_2]^-$ supply both of the necessary redox equivalents for the net $2e^-$ transformation. (2) The $[Co^{III}(ap^{Ar})_2]^-$ complexes are 200−400 mV less reducing than most cobaloxime(I) species.[5] This permits reactions of $Co^{III}(Et)(isq^{Ph})_2$ with organozinc reagents to give the products of $2e^-$ reductive elimination, also without a change in cobalt oxidation state. The redox-active ligand-mediated reactions are therefore complementary to recently reported ligand-derived oxidative addition and reductive elimination at d^0 metal complexes.[4b−d] Notably, the surprising proclivity for $2e^-$ reactions over $1e^-$ redox forms a basis for development of new well-defined first-row metal catalysts for selective cross-coupling cycles.

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Supporting Information Available: Complete synthetic and experimental details; selected UV−vis absorption spectra; collected reaction rates for organohalide addition to $[Co^{III}(ap^{Ph})_2]^-$; tabulated yields from organozinc halide coupling reactions; X-ray crystallographic data and files in CIF format. This material is available free of charge via the Internet at http://pubs.acs.org.

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(9) The slow reaction of $[Co^{III}(ap^{Ph})_2]^-$ with $PhCH_2X$ likely further highlights the sensitivity of the reaction to steric hindrance.
(10) Reactions with haloalkanes that are probes of radical intermediates (*e.g.*, (bromomethyl)cyclopropane) were inconclusive because the ^1H NMR spectrum of the organometallic alkylcobalt(III) products are broadened by trace quantities of the $S = {}^1/_2$ $Co^{III}(ap^{Ar})(isq^{Ar})$ decomposition product.
(11) The speciation of reduced cobalt complex is concentration dependent. $[Co^{III}(ap^{Ph})_2]^-$ reacts rapidly with PhZnBr to form an equilibrium adduct that we tentatively formulate as $[Co^{III}(Ph)(ap^{Ph})_2]^{2-}$.
(12) In both reactions the balance of the cobalt-derived ethyls was not found. These may form butane, which is not quantitated by the GC-MS method used.
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